FINAL REPORT

Documentation and Analysis of Tree Root Extent and Behavior Along and in Levees and Floodwalls in the New Orleans District

January 2008

US ARMY CORPS OF ENGINEERS
NEW ORLEANS DISTRICT
Tree Root Study Along Levees and Floodwalls
W912P8-07-D-0040, Task 0002/Final Report

JESCO ENVIRONMENTAL & Geotechnical Services, Inc.

LSU AgCenter Research & Extension

GEC G.E.C., Inc.

JESCO ENVIRONMENTAL
& Geotechnical Services, Inc.

January 2008

Contract No. W912P8-07-D-0040
Task Order No. 0002

Documentation and Analysis of Tree Root Extent and Behavior Along and in Levees and Floodwalls in the New Orleans District

Final Report

Submitted to

U.S. Department of the Army
New Orleans District
P.O. Box 60267
New Orleans, Louisiana 70160-0267
ATTN: Mr. Stephen F. Finnegan

Submitted by:

JESCO Environmental &
Geotechnical Services Inc.
1701 South Thibodeaux Road
Jennings, LA 70546
DUNS #948076989
Contact: Tom Cousté P.E.
Hubzone and Woman Owned Small Business
Telephone: (337) 824-9074 Fax: (337) 824-9076

Table of Contents

Figures

Tables

Section

Appendices

Section

Executive Summary

Introduction

LSU Agricultural Center, School of Renewable Natural Resources (SRNR) personnel were responsible for study design, protocol development, primary data collection, data analysis, and report generation. SRNR personnel included Dr. Jim L. Chambers, Weaver Brothers Endowed Professor for Excellence in Forestry; Dr. Thomas J. Dean, Professor of Forestry; Melinda S. Hughes, Senior Research Associate; Christopher B. Allen, Research Associate SRNR; Fugui Wu, Forestry Ph.D. Candidate; and Steven Wright, Master of Agriculture Candidate SRNR.

JESCO handled the primary contract for the project. Mr. Tom Cousté P.E. of JESCO provided project management. Additionally, JESCO and GEC assisted in data collection, provided equipment and advice as needed, provided equipment operators, handled logistics of sampling and material gathering, and coordinated with the Corps of Engineers.

Project Introduction

The New Orleans District, U.S. Army Corps of Engineers (MVN) requested data gathering and analyses of tree root extent and behavior to provide empirical data in support of vegetation management guidelines for Federal and non-Federal levees and floodwalls. The root study project area was broadly defined as the 1,300 miles of Corps of Engineers levees in the New Orleans District of southern Louisiana. The study and data collection focused on tree removal project areas in the metropolitan area including the New Orleans Lakefront levee, Orleans Avenue Canal levee and floodwall on the City Park side, the London Avenue Canal, and the 17th Street Canal. Additional supplementary data were taken on current and abandoned levee reaches along the Mississippi River in south Louisiana. The root study did not include geotechnical analyses of tree roots relative to levees and floodwalls.

Scope of Work

Root study tasks were broken down in three separate phases or tasks.

- Phase or Task 1 – Literature Review
- Phase or Task 2 –Data Collection Protocol
- Phase or Task 3– Data Collection and Analysis, Final Report Preparation

Phase 1: Literature Review

In general, SRNR personnel conducted a literature review synthesizing the information found and its potential relevance to root extent and behavior along and in compacted and disturbed soils, as they occur along and within levee systems in this study. The literature review included research on root barriers and their potential use and effectiveness, and also discussed the potential for use of remote sensing techniques in future work.

Phase 2: Data Collection Protocol

Field data was collected by selected species and tree size (diameter and height) and include information on soil texture, soil strength by depth, and other defining parameters. The variability of root growth by species, tree size, and environment is extremely high and the nature of this project which involves the integrity of levees and floodwalls for southern Louisiana was particularly sensitive in nature. Consequently, initial work was considered a first estimate regarding detailed information about data quality. This work provides a metric necessary to determine sampling intensities for defined data quality objectives for more detailed study.

Initial work included measurements, with standard sampling procedures, distance, depth, and distribution of roots along and within levees and floodwalls. Work included a variety of species and tree sizes. Species included American sycamore, live oak, water oak, pecan, baldcypress, pine (generally slash pine), sugarberry, Drake elm and Chinese tallow tree as available Three tree size categories, based on diameter (12 to 19 inches, 20 to 36 inches, and 36 inches and above), were used to ensure collection of data across a range of stem diameters (tree sizes) as potentially related to root extent and behavior within species. Investigators took advantage of tree distributions at varying distances from the toe of levees and floodwalls to provide a composite picture of root extent by species and size, while protecting the integrity of the existing levees and floodwalls.

The primary technique for documenting root extent and behavior was root-profile mapping of trench sidewalls. Measurable dimensions of measurement trench surfaces were a maximum of 3 ft deep and 10 feet in length and ran parallel to levees or floodwalls. Most trench root-profile walls began at least 9 ft away from subject trees between the tree and the levee. Additional trenches were added at approximately 6 ft intervals until the majority of major roots (larger that 0.5 inches in diameter) were surpassed. Abandoned Mississippi River levee sections in south Louisiana were used to provide some of the information regarding the presence of deep roots (roots at depths greater than 3 ft). Observational information was obtained from the ongoing Corp root removal program when timing and logistics worked out with Corp contractors. Lack of quality control, time, and logistical constraints did not allow data to be collected along with the ongoing root removal program. Observational information was collected from trenches near tree stumps or near standing trees to be cut in proximity to levee toe. A

Corp contractor assisted in excavation of a number of initial observational trenches to help with protocol development and to explore for the possibility of deep roots.

Phase 3 – Data Collection, Data Analysis, and Final Report Preparation

Seventy-nine trees were selected for root-profile wall mapping. Root extent of 54 trees along levees on the east and west side of the 3 outfall canals in northern New Orleans and 9 trees along the protection levee on the Pontchartrain lake front were sampled. Root extent of 16 trees along the west protection levee along the Mississippi River, north of White Castle were also sampled. All sampling occurred between April and June of 2007. Study tree diameters ranged from 13 inches for the smallest trees to 65 inches, but most trees ranged between 15 and 36 inches in diameter.

Trees selected for sampling root extent were located within a corridor extending from the toe of the levee to a distance where roots might extend. The outer boundary of the corridor was based on past measurement experience with a particular species and size combination. Ideally, trees were isolated enough to expect only the roots from the sample tree to be sampled on the root-profile wall, though roots of other species probably also protruded from the sample face on some occasions. Within a particular species, the sample trees well represent the range of sizes encountered near the outfall levees. In addition to stem diameter, total height of intact trees was measured. Twenty-one trees were represented as remaining stumps at the time sampled. They had been cut prior to the initiation of this study. As mentioned in Phase II, radius of the live crown in the direction of the levee was measured with a 100-ft tape. Crown diameter was also measured in the direction of the levee and at right angles. These two diameters were averaged for the tree. Mean height of the sample trees ranged from 33 ft to 80 ft - the smallest tree was a 28-ft tallow tree and the tallest was a 110-ft sycamore tree.

Radial root extent was estimated by counting roots protruding from one face of shallow trenches excavated with a small excavator. Trenches were large enough to accommodate measurement root-profile walls that were 10-ft long and 3-ft deep. The right-of-entry corridor was often narrower than the corridor of roots with diameters of 0.5 inches or larger originating from candidate trees. For trees within the right-of-entry corridor, the first root-profile wall was generally excavated approximately 9 ft from the base of tree. For trees outside the right-of-entry corridor, the first root-profile wall was created at the toe of the levee. Subsequent trench walls were excavated at approximately 6-ft intervals from the previous wall toward the ridge (shoulder) of the levee. Sampling was generally considered complete when less than 2 roots in the lowest root diameter category were present. A total of 217 trenches were excavated.

The number of roots counted in the 0.50 to 0.99-inch diameter class was nearly one order of magnitude greater than the number of roots counted in next two diameter classes; they exceeded the number of roots greater than 2.0 inches by two orders of magnitude (Table 4). While the number of roots counted should be a function of species, the number counted for each tree is a function of the relative frequency of each species represented in the sample. Normalizing according the number trees selected by species: slash pine had the highest number of roots counted (44.9/tree on the root-profile wall surface) and sugarberry had the fewest number of roots counted per tree (13.7/tree on the root-profile wall surface).

Root growth can be physically restricted by the soil's resistance to penetration or soil strength. This resistance in this study was estimated with a pin penetrometer. Normally, soil strength will increase with soil depth as a result of clay accumulation. Soils in the New Orleans area and along the Mississippi River levee are relatively young marine or river deposits mostly eliminating the vertical gradient in soil strength in more weathered soils. In addition, levees are constructed mostly from homogenized and compacted fill, minimizing variation in soil strength. The effect of the homogenizing factors is clearly evident in the penetrometer readings. Some heterogeneity is evident in the soils: penetrometer readings as readings ranged from a minimum of 1.5 to 3 to a maximum of 15.5 to 20. Mean soil strength did not vary predictably among horizons or among levees.

Mean penetrometer readings varied with textural class, with highest readings for finely textured soils (clay) and lowest readings for silty soils and coarse texture sands. The textural class of the soil was determined at successive 1-ft intervals on the root-profile wall using a decision key. Trenches were predominantly excavated in two textural classes: clay and silty clay. The next two frequently encountered textural classes were clayey silt and silt. The frequency of these texture classes is consistent with soil origin in New Orleans and along the Mississippi River. It is also consistent with the geotechnical requirements of the levees. Sand was encountered on a few levees (Pontchartrain lakefront and the southern end of the London Ave canal). A layer of weathered brick was found in trenches excavated on the north end of the London Ave canal. Other items found in trenches were buried baldcypress stumps, large pieces of concrete and old tile drains.

For all species, the number of roots greater than 0.5 inches in diameter decreased with distance from the base of the tree. Roots greater than 1.0 inch also decreased with distance from the tree, but since substantially fewer roots in the larger size classes protruded from the root-profile walls, the pattern was far less pronounced. Because so few roots greater than 1.5 inches in diameter were counted on the 30 ft2 root-profile wall surface, no apparent relationship existed between number and distance.

Factors Influencing Root Number and Extent

To determine factors influencing the number of roots above the three minimum-size categories, correlation coefficients were calculated between the logarithm of root counts and distance, and other tree and soil properties. The counts were transformed because the decline in root counts with distance from the tree resembled an exponential decay function. Distance was consistently correlated with the logarithm of counts for all three minimum size categories. For roots greater than 1.5 inches, distance was the only variable that correlated with the log of counts. For roots greater than 1.0 inches, stem diameter was also significantly correlated with root counts. For roots greater than 0.5 inches, stem diameter, tree height, and a simple volume index based on diameter and height were also correlated with root counts. For each diameter category, the number of roots protruding from the root-profile walls varied with species, decreased with depth, and increased with stem diameter. Roots greater than 0.5 inches decreased with increasing soil strength. Variation in the number roots per root-profile wall was high and correlations between explained only 30% of the variation. For each root diameter category, the number of roots protruding from the root-profile walls varied with species, decreased with depth, and increased with stem diameter.

The distance from the tree, where the number of roots protruding from a root-profile wall was one or less, was assumed to be the maximum radial extent of roots emanating from the subject tree. The actual tips of the roots were not located. Maximum extents were determined for each of the root diameter thresholds. Correlation coefficients between maximum root extent and tree characteristics were generally significant for roots in all three diameter categories. Maximum root extent was not significantly correlated with soil strength for any diameter threshold. For roots greater than 0.5 inches and greater than 1.0 inches, the index of stem volume (D2H, representing overall tree size) showed the highest correlation with maximum root extent; tree height and crown size were the next most correlated variables. For roots greater than 1.5 inches in diameter, crown diameter showed the highest correlation with root extent.

The maximum radial extent of the roots is related to tree species, but the specific rankings vary by the diameter thresholds of the diameter class. The furthest average extent was seen in roots > 0.5 inches in diameter for pecan. Sycamore roots extended the furthest for roots greater than 1.0 and 1.5 inches. The maximum extents of sugarberry roots in the various size classes were approximately half the extent of the pecan and sycamore roots. The maximum extent of water oak roots greater than 1.0 and 1.5 inches were nearly the same as sugarberry. While specific species rankings varied with each diameter threshold, species were consistently in the top or bottom halves of the rankings, with exception of baldcypress.

The edge of the crown is commonly thought to demarcate radial root extension. If true, the slope between the maximum radius of roots and crown radius would be one. Our estimate of maximum root extent regressed against crown radius had slopes of 0.5 and smaller for three categories of root sizes. Plots of the resulting equations indicate that on average, roots greater than 0.5 inches in diameter do not extend past the edge of the crown, at least not in the direction of the levee. Roots greater than 1.0 inch and greater than 1.5 inches in diameter extend on average to half way between the stem and the edge of the crown. However these relationships only explain between 10 and 33 % of the variation in root extent.

Given the high variation in root extent observed in this study, probabilities of how far roots extend may be more informative than deterministic approaches such as the correlation and regression analyses results above. Probabilities are determined by fitting probability density functions to frequency data. With cumulative probability function, the distance from the tree encompassing specific cumulative fractions of root within a volume of soil 3-ft deep and 10-ft across can be calculated. Half of the roots greater than 0.5 inches in diameter protruding on the root-profile walls were within 12 ft of the tree (levee side) for all but pecan and sycamore. Pecan required the longest distance to account for 50% of the roots greater than 0.5 inches counted on the root-profile wall: 15 ft. Fifty percent of the roots greater than 0.5 inches were within 11 ft of the tree for baldcypress, slash pine, sugarberry, and water oak (Table 10). Ninety-five percent of the roots greater than 0.5 inches in diameter were counted on the root-profile walls within 37.8 ft of pecan trees. Ninety-five percent of the roots greater than 0.5 inch in diameter were counted on root-profile walls at distances of less than 28 ft for live oak, tallow, and water oak, and at distance of less than 19 ft for baldcypress, slash pine, and sugarberry. The paucity in the number of roots greater than 1.5 inches that were counted on the root-profile walls produced poor fits of the Weibull function to the data collected for water oak. Half of these roots can be expected within about 13 ft of the tree. The closest distance where half of the roots in this size class were counted was slash pine at 9 ft.

Homogenization of levee soils did not really allow a full comparison of soil textures on root extent. Differences were noted between root extent on the Mississippi River levee soils and the New Orleans area levee soils, but there was a significant interaction with root diameter class. Interpretation is limited at best and species compared was substantially fewer.

Deep Roots

An additional exploration of roots was conducted on abandoned sections of levee along the Mississippi River to reveal the possibility of deep root presence. Ten trees representing 5 species were selected. For the selected species, trenches were excavated to the limit of the mini-excavator used (about 7.5 to 8 ft deep). When roots were found, some were traced to the limit of the equipment used. At least 20 roots were encountered in efforts to explore roots below 4 ft in the soil below these trees. The conclusion is that large diameter roots do exist below the 3 ft depths we measured in the root-profile walls during the current study. These roots seem to be uncommon, but the true extent and number are unknown.

Data Gaps and Future Research

The largest deficiency in the study was related to the paucity of roots in the larger diameter classes (within the 10 ft trench per tree), especially those greater than 1.5 inches in diameter and the ability to document roots at depths exceeding the 3 ft limit imposed on the study. The number of species included in the study appeared representative of the dominant species along the New Orleans outfall canals. Live oak, pecan, and water oak were sampled most frequently. Sugarberry was numerous along the levees, but few were sufficiently isolated to adequately sample roots for an individual tree.

The report outlines many of the existing data gaps and approaches to gathering such information. The following additional research is needed:

- Additional root-profile walls for the underrepresented species would strengthen species comparisons.
- Estimates of maximum radial extent of roots of the various size thresholds are extremely variable. Increase the number of trees sampled and continue development of the probability of roots of a given minimum size class that will extend past a specified distance.
- Compare root extent of pairs of trees, those growing on a typical urban soil and a twin tree with roots growing into a levee should be made. More root information outside the levee influence is needed for comparison.
- Three aspects concerning soils effects on root growth need further study for predicting root behavior near levees: (1) the effect of compaction of homogenized soils; (2) the effect of homogenization; and (3) the effect of soil texture.
- Geotechnical tests of the effect of large, deep roots on levee integrity are needed to determine the actual risks these roots have on levee failure, especially for trees that die. Construction of a physical model should be possible to explore the effects of root channels on outfall levees.
- Collect data on deeper roots to complement geotechnical tests and physical models above. Deeper roots do occur in and under levees.
- Another important question that could not be addressed in this study is how far a tree must be from the levee toe to avoid a tree falling in high winds and the root ball destroying the base of the levee.
- Predicting the vulnerability of individual trees to windthrow is extremely difficult because tree failure is not a function of mechanical properties of tissue or even individual organs such as stems and branches but a function of the structure and developmental history of the entire tree. Suggestions for future investigation are provided in the report. An online database link with over 5000 tree failure reports and information on data collection guidelines is provided.

Documentation and Analysis of Tree Root Extent and Behavior Along and In Levees and Floodwalls in the New Orleans District

Personnel Introduction

The LSU Agricultural Center, School of Renewable Natural Resources (SRNR) personnel were responsible for study design, protocol development, primary data collection, data analysis, and report generation. SRNR personnel included Dr. Jim L. Chambers, Weaver Brothers Endowed Professor for Excellence in Forestry; Dr. Thomas J. Dean, Professor of Forestry; Melinda S. Hughes, Senior Research Associate; Christopher B. Allen, Research Associate SRNR; Fugui Wu, Forestry Ph.D. Candidate; and Steven Wright, Master of Agriculture Candidate SRNR.

JESCO handled the primary contract for the project. Mr. Tom Cousté P.E. of JESCO provided project management. Additionally, JESCO and GEC assisted in data collection, provided equipment and advice as needed, provided equipment operators, handled logistics of sampling and material gathering, and coordinated with the Corps of Engineers.

Project Introduction

The New Orleans District, U.S. Army Corps of Engineers (MVN) commissioned data gathering and analyses of tree root extent and behavior to provide empirical data in support of vegetation management guidelines for Federal and non-Federal levees and floodwalls. The root study project area was broadly defined as the 1,300 miles of Corps of Engineers levees in the New Orleans District of southern Louisiana. The study and data collection focused on tree removal project areas in the metropolitan area including the New Orleans Lakefront levee, Orleans Avenue Canal levee and floodwall on the City Park side, the London Avenue Canal, and the 17th Street Canal. Additional supplementary data were taken on current and abandoned levee reaches along the Mississippi River in south Louisiana. The root study did not include geotechnical analyses of tree roots relative to levees and floodwalls.

Investigated Locations

The JESCO Environmental & Geotechnical Services Inc. (JESCO) collected trenching data in the following areas:

- London Avenue Canal, New Orleans, LA – Sampled sections of the east and west levees of the London Avenue Canal starting from Robert E. Lee Boulevard and ending 2500 feet north of Gentilly Boulevard.
- Orleans Canal, New Orleans, LA – Sampled the section from Harrison Avenue to Robert E. Lee Boulevard on the east levee. Due to the location of Orleans

Avenue to the west levee of Orleans Canal, the west levee did not have any acceptable trees for this study.

- Lakefront Levee, New Orleans, LA – Sampled the north side of the levee at the section starting at Marconi Drive and ending at the intersection of the Lakefront Levee and Lakeshore Drive (approx. 1200ft).
- 17th Street Canal, New Orleans, LA – Sampled the section from 10th Street to 40th Street on the east levee. Sampled the section from Pink Street to Violet Street on the west levee. Also sampled the section from Cherry Street to London Avenue on the west levee.
- Mississippi River levee Sections 5155, 5070, and 4990, Bayou Goula, LA – Sampled the section from Augusta Street (30° 12' 22"N, 91° 10' 12"W) to Point Street (30° 14' 29"N, 91° 07' 43"W) near the west levee.
- Mississippi River Levee Section 5595, Cannonburg, LA – Sampled the section from Cannonburge Street (30° 11' 45"N, 91° 06' 15"W) to Brou Road (30° 12' 10"N, 91° 04' 11"W) on the west levee.

Project Phases and Tasks

- The JESCO Team (JESCO, LSU, and GEC) were involved in data collection analysis and report production.

Scope of Work

Root study tasks were broken down in three separate phases/tasks.

- Phase or Task 1 – Literature Review
- Phase or Task 2 –Data Collection Protocol
- Phase or Task 3– Data Collection and Analysis, Final Report Preparation

The SRNR personnel above conducted a literature review synthesizing the information found and its potential relevance to root extent and behavior along and in compacted and disturbed soils, as they occur along and within levee systems in this study. The literature review included research on root barriers and their potential use and effectiveness, and it also included the potential for use of remote sensing techniques in future work. School of Renewable Natural Resources (SRNR) scientists (PIs) with the LSU AgCenter developed a protocol for root sampling and data collection, assisted JESCO with data collection, and provided analyses of data on tree root extent and behavior as outlined below, to support the refinement of vegetation management guidelines for Federal and non-Federal levees and floodwalls. When beneficial and feasible to data collection efforts, the documentation efforts took advantage of information produced during the uprooting and removal of trees from various levees and floodwalls as part of the ongoing tree removal program. The data were collected by selected species, tree size (diameter and height) and include information on soil texture, soil strength by depth, and other defining parameters.

Phase 1: Literature Review

A literature review of root growth and behavior is provided in two forms: (1) A synthesis of literature information found and its potential relevance to root extent and behavior along and in levee and floodwall systems in this study and (2) an Appendix with an annotated bibliography summarizing relevant and closely related scientific literature on root extent, and behavior. Both literature reviews also include research on root barriers and their potential use and effectiveness and the potential for use of remote sensing techniques in future work.

Phase 2: Data Collection Protocol

The variability of root growth by species, tree size, and environment is extremely high, and the nature of this project which involves the integrity of levees and floodwalls for southern Louisiana was particularly sensitive in nature. Consequently, initial work must be considered a first estimate regarding detailed information about data quality. This work provides a metric necessary to determine sampling intensities for defined data quality objectives that can be used for more detailed future study.

Initial work included measurements, with standard sampling procedures, distance, depth, and distribution of roots along and within levees and floodwalls. Work included a variety of species and tree sizes. Species included American sycamore, live oak, water oak, pecan, baldcypress, pine (generally slash pine), sugarberry, Drake elm and Chinese tallow tree as available Three tree size categories, based on diameter (12 to 19 inches, 20 to 36 inches, and 36 inches and above), were used to ensure collection of data across a range of stem diameters (tree sizes) as potentially related to root extent and behavior within species. Investigators took advantage of tree distributions at varying distances from the toe of levees and floodwalls to provide a composite picture of root extent by species and size, while protecting the integrity of the existing levees and floodwalls.

The primary technique for documenting root extent and behavior was root-profile mapping of trench sidewalls. Measurable dimensions of trenches were a maximum of 3 ft deep and 10 feet in length and ran parallel to levees or floodwalls. Safety of the trenches to workers was assured by the JESCO and selected safety personnel. Initial trenches generally began near the toe of the levee depending on the distance from the tree to the levee toe and access to property. Most trenches began at least 9 ft away from subject trees between the tree and the levee. Additional trenches were added at approximately 6 ft intervals until the majority of major roots (larger that 0.5 inches in diameter) were surpassed. The order of trenching was be determined by safety procedures. JESCO was responsible for creation of trenches as needed and the surfacing of trenches for root identification and measurement.

Phase 3: Data Collection, Data Analysis, and Final Report Preparation.

JESCO and GEC assisted in data collection, provided equipment and advice as needed, provide equipment operators, handled logistics of sampling and material gathering, attained permissions for rights of ways. They were initially to have the primary responsibility of collection of field data (and to complete a minimum of 80 sample trenches and other requirements set above). Sampling procedures and variation in conditions of levees as well as many changes in the logistics for sampling and time tables for work necessitated LSU personnel participate in all field sampling and added considerably to the overall number of sample trenches (217 trenches). The report includes drawings, tables, and graphics illustrating tree root extent and behavior related to levees. Recommendations are included regarding any additional investigation and documentation needed relevant to tree effects on south Louisiana levees. These recommendations provide additional data needs. Abandoned Mississippi River levee in south Louisiana were used to provide some of the information regarding the presence of deep roots (roots at depths greater than 3 ft.)

Coordination of Activities with Root and Trees Removal Contractors.

Observational information was obtained from the ongoing Corp root removal program when timing and logistics worked out with Corp contractors. Lack of quality control, time, and logistical constraints did not allow data to be collected with the ongoing root removal program. Observational information was collected from trenches near stumps of cut trees and from standing trees to be cut in proximity to levee toe.

Data from Overturned Trees

Data on the size of holes created by trees blown over during a storm is commonly obtained from tip-up mounds created during a storm. However, such trees had been removed before the project started and could not be sampled. In lieu of this opportunity and where feasible, we had hoped to work with Corp contractors removing trees from levee right-of-way or Lakefront areas to pull over mature trees being removed after measuring their diameter and height. Contractor schedule, contracts and the methods used in tree removal by contractors did not allow the collection of this type of data. Report includes information on database available for tree failure data and suggested measurements for predicting outcome from future storms.

Submittables and Period of Performance

The deliverables below with the initial projected timelines were established before the project was initiated. Modifications to the initial schedule were negotiated as logistics necessitated.

a. Preliminary Report (Phase or Task 1).

The initial annotated bibliography will be submitted four weeks after contract is executed for School of Renewable Natural Resources (SRNR) portion of work. The bulk of the literature was included in this submission, however literature searches continued throughout the data collection and analysis period. Additional pertinent literature gathered after this date was included in the interim and final reports and used in the discussion of results.

b. Preliminary Report (Phase or Task 2).

An updated annotated bibliography and standard operating procedures describing field data collection procedures, preliminary data analysis, and evaluation of field techniques was provided approximately 8 weeks after contract was executed for the SRNR portion of the work.

c. Comprehensive Study Report (Phases or Tasks 1-3).

An updated annotated bibliography, full literature review with synthesis of all information found, and a comprehensive draft report of the full project, including data tables, figures was provided. Government review and revision followed. At least 2 weeks will be necessary for revisions after Government comments are received by SRNR PIs.

NOTE: No geotechnical evaluation was performed in relation to tree roots.

Estimated Timeline (April 6, 2007 through July 28, 2007; see details on next page)

Estimated Timeline for Project

Task	Description	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11	Wk 12	Wks 13-16
T1	Annotated bibliography	X	X	X	X	X	X	X	X	X				
T2	Tree selection	X	X			X	X							
T2	Interim Report					X	X							
T3	Data Collection		X	X	X	X	X	X	X	X				
Task	Description	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Wk 6	Wk 7	Wk 8	Wk 9	Wk 10	Wk 11	Wk 12	Wks 13-16
T3	Literature Synthesis						X	X	X	X	X	X		
T2/3	Data Analysis							X	X	X	X	X		
T3	Draft Report								X	X	X	X		
T3	Final Report												X	X
Wk = week; T= phase/task; X = planned period of work														

The following report describes each phase or task of the root study in detail.

Phase I

Literature Synthesis on Root Extent and Root Behavior

Introduction

The subject of tree root extent and behavior is a subject of great interest and discussion in the forestry and urban forest scientific communities, but is much less studied than the above-ground growth and behavior of trees. The hidden nature of roots and the difficulty of access and measurement cause the study of root extent and behavior to lag behind the study of the above-ground portions of trees. Even though roots provide trees critical access to water and nutrients, and roots provide anchorage even in severe environmental landscapes (e.g. steep slopes, hurricane force winds and permanently flooded soils) their study continues to pale against the study of above-ground aspects of tree growth. Much of the scientific literature on tree root extent and behavior involves destructive sampling of roots and often involves removal of trees themselves. This literature synthesis and the accompanying annotated bibliography provide a broad perspective on the subject of tree root extent and root behavior.

The focus of this literature review is to provide a cross section of the scientific literature on tree-root extent and behavior from a variety of perspectives that relate directly or indirectly to understanding the potential maximum extent of tree roots and how tree root behavior is affected by species, tree size, and in different soil environments. In addition, the synthesis explores literature topics relevant to how tree roots might behave in levees and along outfall canals. The literature review also covers some aspects of remote sensing and measurement of roots and documents literature on the effectiveness of root barriers in preventing root growth into unwanted areas. This review contains information primarily from scientific reviews and refereed journal papers from research studies. In addition to the scientific works, some technical notes, proceedings, and other works are reviewed that add to the body of literature on related topics or that may be relevant to levees *per se*.

Maximum Extent and Depth of Roots

Jackson et al. (1996) provided a review of root distributions and root depth in terrestrial biomes. They concluded that desert and temperate forests had the deepest root profiles with 50% of their roots in the upper 12 inches (30 cm) of the soil profiles. Maximum root depth has often been ignored in studies of tree root systems. Stone and Kalisz (1991), in a review of maximum extent of tree roots, blame the lack of good maximum root depth data on several factors. They indicate that early research on tree roots was often concentrated on soils with shallow profiles and mechanical or other barriers to root penetration. This early literature gave the impression that roots were restricted near the soil surface. Since surface soils often contained higher concentrations of nutrients and are the entry point of water, research has been concentrated on roots near the surface. According to Stone and Kalisz, near-surface fine-root production has led researchers to concentrate on surface root absorption of both water and minerals, even though there is growing evidence that deeper roots are important for water uptake and in some cases for nutrient uptake. The majority of the literature on root extent and behavior does not provide data on, or even sample for, maximum tree root depth (Schenk and Jackson, 2005). Schenk and Jackson estimate that less than 10% of the research papers on roots present information on maximum root depth. Sampling for maximum depth is hindered by the high cost in time and money for exploration, and for destruction and safety considerations as well.

A number of recent reviews have presented summaries of the maximum lateral and vertical extent of tree roots (Stone and Kalisz 1991, Schenk and Jackson 2005, Canadell et al. 1996). Hermann (1977) reviewed the literature related to root types and root behavior with respect to soil environment and species. Reports of maximum root depths and radial extent have varied considerably from species to species and site to site. Contrasts of maximum root depths or radial extent among species are not appropriate for the diversity of conditions reported, however, reports of deep and long roots are numerous in the literature. Canadell et al. (1996) summarized observations on over 250 plants species. More than 190 had roots exceeding depths of 6.5 ft (2 m) and some with roots exceeding 65.6 ft (20 m). Several deep-rooted species include temperate forest species with root depths exceeding 14.4 ft (4.4 m) for deciduous species and 24.6 ft (7.5 m) for coniferous species. Heyward (1933) reported a root depth of 14 ft for a longleaf pine (*Pinus palustris)* that was 54-ft tall and only 17 inches in diameter. A lateral root of this tree, growing within a few inches of the surface, reached 71.5 ft in length before taking a vertical angle and extending an additional 3.5 ft. Lateral roots were commonly 1 inch in diameter at a distance of 12 to 15 ft. from the tree. Day (1944) reported aspen root lengths in 18-year-old trees of 47 ft and vertical lengths of 7.5 ft. Even 8-year-old trees had lateral roots reaching 30 ft. Kochenderfer (1973) presented road-cut and strip-mine root profile information on several forest types in West Virginia. The oak-hickory type produced the deepest roots at 13.1 ft (4 m). Jackson et al. (1999) found many tree roots on the Edwards plateau in central Texas reached depths of 16.4 ft to 213.2 ft (5 to 65 m). Plateau Oak (*Quercus fusiformis)* and *ash Juniper* (*Juniperus ashei)* produced the deepest roots in the Edward plateau area. Watson et al. (1999) explored the root properties of radiata or Monterey pine (*Pinus radiata)* and found maximum root depth of 10.1 ft (3.1 m) and radial extent of 32.8 ft (10.0 m). Both of these values were greater than reported by Stone and Kalisz (1991, see below). Millikin and Bledsoe (1999) presented excavation data on blue oak (*Quercus douglasii)* in the northern Sierra Nevada foothills. They noted the lateral extent of woody roots was highly plastic depending on growing conditions in the soil environment, however, they also found distance from the tree did not significantly affect fine root biomass. Falkiner et al. (2006) noticed roots of *Eucalyptus* and spotted gum (*Corymbia)* reaching depths of 5.2 ft to 6.5 ft (1.6 to 2.0 m) even in degraded saline soils of southeastern Australia. Gifford (1966) explored aspen root systems in Utah. In trees sampled, he found maximum root depths of 9.5 ft and a maximum root spread of 27 ft. However, the majority of roots in these trees occurred above a 4-ft depth. Brown and

Woods (1968) used radioiodine to approximate the distance of lateral roots from trees of a wide variety of species growing in forest environments. They found maximum distances of uptake (root length) ranged from 31.8 ft for dogwood to 33.3 ft for red cedar. Maximum distances for the white-oak group was 38.1 ft: for the black-oak group the distance was 11.7 ft. Maximum distance for hickory was 31.6 ft.

Stone and Kalisz (1991) surveyed the literature for indications of maximum vertical and lateral rooting extent. Their work was based on actual reports, communications, and their own observations of root extent. In some cases measurements of soil water changes were used to deduce maximum root extent. They omitted typical or average depths whenever actual maximums were provided and they omitted commonplace values of less than 4.9 ft (1.5 m) for depth and 22.9 ft (7 m) for radial extent. Stone and Kalisz suggested that the largest values they report for a species are probably near the maximum, but that the smallest values were not likely the actual maximum values. They present tables summarizing the maximum root extent for 49 families, 96 genera, and 211 species of trees. From their work we know that even relatively young trees can have extensive root systems (e.g., slash pine (*Pinus elliottii)* at age 5 with radial root extent of 32 ft, and 4-year-old radiate or Monterey pine (*Pinus radiate)* with a root depth of 8.5 ft). They reported results for several tree species common to the New Orleans area (none of the original data were from Louisiana) with the maximum root depths and greatest radial root lengths, respectively, as follows: slash pine (*Pinus elliottii)*: 15 ft (4.6 m) and 59 ft (18.0 m); live oak (*Quercus virginiana)*: radial length of 100 ft (30.5 m); pecan (*Carya illinoinensis)*: greater than 9.8 ft (3.0 m) and greater than 32.8 ft (10 m); cottonwood (*Platanus occidentalis):* 6.8 ft (2.1 m) and 49.2 ft (15.0 m); and hackberry (*Celtis occidentalis)*: 8.2 ft (2.5 m) and 41.3 ft (12.6 m).

Danjon et al. (1999a) found a strong relationship between stem straightness (ranked from 0 to 20) and large-root depth. They cited results from Auberlinder (1982) indicating a similar relationship for maritime pine. In that study, unstable trees had more shallow root systems with vertical roots averaging 20% of the total cross-sectional area, while more stable trees had nearly 40% of the total root cross-sectional area in deep roots.

Again, maximum root depth is not measured in most studies of tree roots and even radial extension measurements are limited by sample size, resource logistics, and apparent, rather than actual root extent. From the literature surveyed, root extent investigations into levees are even more restricted. Questions of potential root channels or piping produced by decaying roots, highlights the need for more in-depth investigation of root extent and root behavior near and in these levee systems.

Species and Tree Size

As Hermann (1977) emphasized, a review of tree root extent and root behavior covers an enormous range of site conditions, climates, and other influencing factors. Root growth of a species varies widely across sites; therefore, species comparisons are probably not wise except under reasonably controlled conditions. While values for various species are important, it is also important to realize that local conditions of root environment probably play more of a role in maximum rooting extent than species. Even so, some comparison is useful. Information from specific studies generally compare species growing on the same general soil conditions, however, keep in mind that roots can be influenced by small changes in microenvironment, especially changes in root penetration resistance (*e.g.* soil crack, fractures, nutrition, changes in density, and anoxic conditions among others). Hermann's 1977 review cited a number of papers which concluded that differences in root behavior, root form, and extent within species were high and that the differences were often related to site differences or, in some cases, genetic differences. Specific studies exploring the causes for the differences in root growth within species are rare . Most references reporting causes of species differences seem to be based more on supposition than evidence.

Sitka spruce lateral root development that took place within the first 8 years determined the structural root system of the trees at 34 years of age (Coutts and Lewis 1983). Larger roots and some minor roots survived across this time frame. Lateral roots of both lodgepole pine and Sitka spruce were often plagiogravitropic and grew upwards until they were signaled to level-off or grow downward. Thus, the roots tended to remain in the nutrient rich surface soils (Coutts and Nicoll 1991).

Drexhage et al. (1999) characterized the sessile oak (*Quercus petraea)* root system of 20- and 28-year-old trees as a "heart-sinker" root system. This root morphology has horizontal lateral roots and a taproot with both vertical and oblique roots. Oblique roots characterize this type of system. Some horizontal roots change to oblique roots away from the oaks and some oblique roots become vertical. Once direction changed individual roots tended to maintain the same direction. The authors indicated a strong relationship between root architecture and stem diameter at breast height (4.5 ft, DBH), and between DBH and the amount of biomass allocated to the surface root system. Danjon et al. (1999b) digitized root systems of sessile oak (*Quercus petraea)* and maritime pine (*Pinus pinaster)*. The oak had a stronger more oblique and vertical root system than the pine. Fleischer et al. (2006) compared root distribution of Norway spruce (*Picea abies)* and European beech (*Fagus sylvatica)*. They performed a two-dimensional analysis with depth and noted a stronger clustering of roots in small clusters for spruce and a weaker clustering of large cluster regions in beech. Beech roots tended to avoid overlap. In a study of tropical tree species, Crook et al. (1997) suggested that only buttressed trees produced sinker roots and normally tapered trees produced more lateral roots. Roots of buttressed trees were not round, but instead up to eight times thicker than wide in cross section. McElrone et al. (2004) noted an important relationship between average tree xylem vessel diameter and individual root depth in each of four tree species. Individual root depths were highly positively correlated with average root xylem vessel diameter.

Le Goff and Ottorini (2001) noted a high correlation between tree diameter and root biomass in European beech (*Fagus sylvatica)*. Regression equations accounted for 99% of the variation in coarse and fine root biomass. Bolte et al. (2004) studied root systems in mixed Norway spruce (*Picea abies)* and European beech (*Fagus sylvatica)* stands in northwest Germany. They sampled trees from a number of areas and across a range of tree diameters: from 6.2 to 28.9 inches (16 to 74 cm) for spruce and from 1.6 to 20.7 inches (4 to 53 cm) for beech. Using regression models of the relationship, they revealed what appeared to be strong positive relationships between tree diameter and the coarse-root biomass of the trees. The R^2 (variation accounted for by the models) was very high in spruce (0.92) and in beech (0.94). However, the root: shoot ratios were 1.2 to 3 times higher in spruce than in beech.

According to Hermann (1977) the most apparent changes with age are the proportion of long and short roots. Several other authors have mentioned changes in root development with age, but it is often associated with different sized trees within the same stands or from stands of different ages on different sites, so differences could be just as easily related to differences in size or in environment. In the review by Hermann (1977) root growth changes were contrasted among species across ages, but Hermann noted that comparisons among species were not meaningful at the level of available data. He did, however, make a number of comparisons and indicated that changes in root development, rooting depth, and root type changed in species over time. Age of change differed widely with species. McMinn (1963) studied the root systems of 28 Douglas fir (*Pseudotsuga menziesii)* in four stands of varying slopes and soils conditions. These trees varied in age from 10 to 55 years. They reported that total length of the root systems increased with age and crown size. They also found that root length and complexity of root branching increased from suppressed to intermediate and again to dominate crown class occupants for trees of the same age-class.

Root growth of tree species may also be affected by competition from adjacent trees of different species. Work by Schmid and Kazda (2001) found that in monospecific stands of beech and spruce, the roots of each species exceeded the maximum measurement depth of 3.2 ft (1 m). However, in mixed stands of the two species, large spruce roots failed to exceed 3.9 inches (10 cm) in depth. Radial root growth of beech exceeded that of spruce in both mixed and pure stands.

Soils and the Soil Environment

Soil--root interactions are mentioned frequently in the literature, but few, if any, papers actually compare root behavior and extent in treatment-based studies of soil texture. Instead most reports compare general or measured characteristics on soils across different forest types, climate, and stand age. These comparisons do not provide direct information on the actual differences and their causes.

Coutts (2004) explored tree roots in relation to slope stability in stressed environments. He emphasized that soil--root interactions are very important, and although tree roots may anchor a species well on one soil, the same tree species may fail on other soils. Authors often restrict studies and thus statements related to tree root growth to specific soils. For example, Di Iorio et al. (2005) concluded that on sloping sites with clayey soils, root symmetry was influenced by several additional environmental factors, including soil compaction. They cautioned that root growth extent, behavior, and mechanical strength are highly dependent on soil type, but did not provide any evidence of the differences in effects among soil types.

Falkiner et al. (2006) reported differences in deep rooting behavior of two species on contrasting soils near the capillary fringe of the water table. Spotted gum (*Corymbia maculate)* and rose gum (*Eucalyptus grandis)* roots behaved differently, with rose gum showing an increased root volume as the roots approached the capillary fringe near 5.2 to 6.5 ft (1.6 to 2.0 m) on both sandy and clayey soils. However roots of rose gum were found to increase in numbers and root length density in the deep soil layers. On the site with sandy soils with low salinities, the greatest root length density (L_v) and greatest number of roots in the lower soils horizons occurred at the maximum measurement depth. However, on the clayey, higher salinity soil, L_v and root numbers declined again just above the capillary fringe. The authors indicated rose gum is sensitive to salinity, but that high clay content may have played a role in root numbers and growth. Differences in rooting in the capillary zone just above the water table paralleled water uptake in this zone. In West Virginia, roots of the oak-hickory forest type were found at depths greater than other forest types studied. In the Gilpin soils, roots were found as deep as 13.1 ft (4 m). In the Ernest soils, number of roots increased in blue-grey clay soil layers (Kochenderfer 1973). In these forests, greater numbers of roots were found in lighter textured soils at shallow depths; however, numbers of large roots actually increased in blue-grey clays or the fractured portion of white silty layers of the Ernest and Gilpin soils. Kochenderfer found the existence of root channels in these soils and some of the root channels had finer roots growing within them.

Soil water content and soil water movement are affected by hydraulic lift (movement of water upward from deeper soil zones through tree roots and out into shallow soil layers) and hydraulic redistribution (both downward and upper movement of soil water) by the tree roots of some species. Brookes et al. (2002) found ponderosa pine (*Pinus ponderosa)* trees were capable of hydraulic redistribution from a depth of more than 6.5 ft (2 m) during relatively dry periods. Both ponderosa pine and Douglas-fir had large sinker roots and were able to provide hydraulic lift Burgess et al. (1998) were able to demonstrate hydraulic redistribution in species of silk oak (*Grevillea)* and *Eucalypus*. Burgess et al. (2000) demonstrated reversible water flow in roots of banksia (*Banksia prianotes)* and water exudations from roots. These findings strongly support tree root redistribution of water in soils. Burgess and Bleby (2006) suggest that the hydraulic redistribution they found in several Australian tree species may support tree root growth in soil zones that would normally be dry during dry periods. Hydraulic redistribution may be important in supporting tree root growth within levees. The steeper slopes and exposure to sun reduce wetting during rains and decrease moisture during sunny periods. Jackson et al. (1999) used DNA sequence variation to identify the roots of various tree species with deep roots penetrating into cave ceilings on the Edwards plateau of central Texas. They found tree roots penetrating to depths of 16.4 to 213.2 ft (5 to 65 m). They suggested that these deep-rooted tree species could supply water to surface soil regions that would assist in other plant species survival under otherwise dry conditions. Caldwell et al. (1998) summarized evidence for hydraulic lift and suggested that it may occur in many species.

McKee (2001) looked at root proliferation within old root channels in Mangroves on peaty soils. She used artificial tubes placed in these soils to simulate different soil conditions. She found roots proliferated when they found tubes with higher nutrient levels, suggesting that new roots entering old root channels proliferate to take advantage of the increased nutrient supply. When tubes were invaded with roots, those with higher nutrient levels produced 6 times more roots than empty tubes or tubes with sand. McMinn (1963) reported hollow root channels from decayed roots under Douglas fir (*Pseudotsuga menziesii)* 40 to 50 years of age. These root channels had younger roots growing in them.

Schenk and Jackson (2005) used data sets from around the world to map and predict the presence of deep roots. Trees were 4 to 6 times more likely than other plants to develop deep roots. Schenk and Jackson defined deep rooted plants as those with at least 5% of their root system at depths of 6.5 ft (2 m) or more. The likelihood of plants having deep roots was greatest for those in fine and coarse textured soils (but not medium-textured soils).

According to Drexhage et al. (1999), root system architecture is often determined by tree size (diameter) when soil properties are unrestrictive. Nicoll et al. (2006b) assessed the effects of species, rooting depth, and soil on the overturning resistance of trees. Their results indicate an interaction between rooting depth and soil types regarding degree of anchorage within tree species. The data set was most complete for sitka spruce (*Picea sitchensis).* Deeply rooted Sitka spruce was anchored best on free-draining mineral soils and on gleyed mineral soils. For medium-rooted trees, gleyed and peaty mineral soils were best. For shallow-rooted trees, deep peats had the best anchored trees. For other species, soil group combinations differed, but for the same rooting depth, other species had lower anchorage than Sitka spruce. Results revealed three-way interactions among species, soil group, and rooting depth for other species. Dupuy et al. (2005a) used a simulation program to evaluate the response of different root system types to soils of various physical properties. The results indicated that heart- and tap-root system types would provide the best tree anchorage on all soils, but that the heart-root system was best on clay type soils and the tap-root system was better for sandy type soils. Their simulation also predicted herringbone- and plate-root systems would have only half the resistance to overturning than the two previous root types. General density functions have been used by Dupuy et al. (2005b) in conjunction with mathematical representations of root systems to test models relative to actual root system characteristics for 50-year-old maritime pine (*Pinus pinaster)* trees. Tests against 2-D maps confirmed the ability of general density functions for constructing models of tree root architecture in the pines. According to the Dupuy et al. this method will allow local morphological characterization within a given soil volume.

Wind Effects on Root Growth and Uprooting of Trees

Strong winds and prevailing wind direction must be countered by tree adaptations that protect the integrity of the tree in these environments. Studies of the effects of wind on tree and root growth are often conducted in areas with high winds, such as coastal areas or hilly and mountainous areas. Uprooting of trees and resistance to uprooting are important where trees are allowed to grow on or near levee systems. Therefore, much of the information derived in wind related studies has potential application to evaluating tree placement along levee systems.

Schaetzl et al.(1990) reported a positive correlation between tree diameter and area of soil disturbance around overturned trees. The initial sizes of pits formed during uprooting were related to tree size and rooting habit. Root depth also increased with tree size up to 40 inches DBH. Stokes et al. (1997) manually flexed tree stems to induce changes in root system characteristics similar to wind induced changes. They noted flexing led to significant increases in coarse root mass and the coarse-root-to-fine-root ratio. Mean root cross-sectional diameter of the flexed tree roots also increased, with the diameter of lateral roots increasing more in the vertical than the horizontal direction. Stokes (1999) studied 5-, 13-, and 17-year-old maritime pine (*Pinus pinaster)* tree anchorage and found the reason for tree failure (breakage or overturning) changed with tree age and size. He found tree anchorage strength increased by the third power of the diameter (DBH). He found that strength of the root also changed with wind flexing of the root system. Resistance to stem breakage was related to the third power of the diameter, while resistance to uprooting appeared related to the square of the diameter. Therefore the relative strength of the root system becomes weaker as the strength of the stem increases.

Crook and Ennos (1996) winched >16-year-old larch (*Larix europea x japonica)* trees to evaluate root breakage and mechanical failure. In 15 of 17 trees winched from the ground, leeward laterals (those growing in the direction of winching) tended to be pushed into the soil and eventually broke. Windward laterals (those growing away from the winching direction) tended to pull out of the soil with sinker roots attached. Strain measurements showed that stress increased toward the tree base. Stokes and Mattheck (1996) suggested that trees with greater branching near the stem base, and those with large, stiff taproots, dissipate forces more quickly and need less developed lateral root systems. Crook and Ennos (1996) concluded that trees with leeward lateral roots are more resistant to bending and those with windward sinkers or taproots have greater anchorage strength. Crook et al (1997) compared anchorage and potential for windthrow in two buttressed and one unbuttressed tree species. They found the buttressed species had sinker roots, but both types had taproots. Anchorage strength of the buttressed species was almost twice that of the unbuttressed species. Strains along buttressed trees were higher than along the laterals of unbuttressed trees. Crook and Ennos (1998) tested 35 *Mallotus wrayi* (no common name) trees varying in diameter from 1.6 to 5.6 inches (4.2 to 14.3 cm) at DBH. They found that anchorage varied by tree diameter, but the variation was not straightforward. Small diameter trees, those less than 2.3 inches (6 cm) in DBH bent, but the roots did not break during winching. Mid-sized tree failed by tree trunk breakage, while large diameter trees failed by root breakage, because the root strength was less than the stem strength. The relationship of anchorage and failure varies by both species and stem size.

Forces causing windthrow, and resistances to it were measured by Coutts (1983). Coutts evaluated the forces and resistances by applying lateral force to stems of sitka spruce (*Picea sitchensis)*. On the leeward side of trees, the root-soil plate acted as a cantilevered beam which determined the distance of fulcrum from the tree. Under increasing load, failure of some portion of the root-soil plate occurred before the maximum force for uprooting was reached. Stability of the root system was linked directly to the mass of the soil-root plate, tensile strength of the roots, soil on the windward side of the tree, and stiffness of the hinge at the fulcrum on the leeward side of the tree. Danjon et al. (2005) studied wind effects on maritime pine (*Pinus pinaster)*. They noted that trees with preferential root volume allocation underwent less damage from high winds. Danjon et al also sampled both undamaged and uprooted trees after a storm and compared preferential root volume production relative to prevailing winds. Trees averaged 65.6 ft (20 m) tall and 14.9 in (38 cm) in diameter. Soils were humus-rich spodosols. Roots greater than 0.38 in (1 cm) were 3-D mapped with a digitizer. Trees that were subject to windthrow had less volume of roots in a confined "root cage." Those roots were shallower (less volume with depth), had a larger proportion of oblique and medium-depth horizontal roots, and had fewer roots in the wind-oriented direction. Roots in wind-firm trees had a 25% increase in roots in the leeward zone of rapid taper with increased sinkers; they also had a 30% increase in surface laterals in the windward direction. Wind reduced roots perpendicular to the direction of the wind. Root systems adapted over time relative to wind exposure (Nicoll and Ray 1996). Nicoll and Ray studied the root-plate dimensions and structural characteristics of 46-year-old Sitka spruce trees growing on a site restricted by a shallow water table. They found the trees had adapted to prevailing winds as the trees moved in the shallow soils. More structural roots were formed on the leeward side of the trees and root system spread was negatively related to the soil-root plate thickness. Coutts (2004) noted that trees growing on slopes are also more resistant to windthrow than trees on flat terrain. He pointed out that overturning, however, is often a critical factor in slope instability (see **Slope effects**).

Putz et al. (1983) used stepwise discriminant analysis to evaluate the effects of various properties on 310 fallen trees on Barro Colorado Island in Panama. Of the variables measured they found that wood strength was the most important factor in determining the type of wind impact. Of the 310 fallen trees: 70% snapped off, 25% were uprooted, and 5% broke off below the ground level; however, the relationship was highly variable such that wood strength could not predict the failure mode of these trees. Stokes and Mattheck (1996) evaluated seven species of trees for root strength characteristics. They found root strength decreased at different rates along roots of different taper. Roots that tapered slowly with distance were relatively stronger than those with rapid taper. Those with slight taper were stronger for longer distances than those with rapid taper. The point of maximum strength is at a distance from the tree corresponding to tree sway from wind movement and the associated maximum root flexing. Stokes and Mattheck (1996) found that the high level of root branching near the stem in heart and tap-root systems led to more rapid dissipation of forces nearer the stem, therefore an investment in production of longer laterals was unnecessary in these species. This may partially explain some of the discrepancies in root properties related to windthrow in different species.

Wind tunnel treatment of seedlings of sitka spruce (*Picea sitchenses)* and European larch (*Larix decidua)* were conducted by Stokes et al. (1995) to detect the effects of wind on root development. Seedlings were used since lateral roots in the early development set the nature of root systems long before maturity. The seedlings were exposed to intermittent wind for 30 weeks from seed. Both shoot and root growth was found to be deflected away from the direction of wind. The side of the seedlings away from the wind produced more plant material. More roots were found in both the windward and leeward sides of the seedlings, with fewer roots perpendicular to the windward direction. In a somewhat similar experiment, Tamasi et al. (2005) subjected seedlings of English oak (*Quercus robur)* to periodic artificial wind for seven months in a sandy, podzolic soil. They then excavated and constructed a 3-D map of the root systems. Seedlings subjected to wind grew more roots and those roots were nearly twice as long as those in no-wind control plots. However, the total root volumes were not significantly different in wind treated versus control seedlings. This same relationship was reported in larger trees by several other investigators for wind- and slope-affected tree root systems. Windward roots were more numerous and longer than leeward roots.

Stathers et al. (1994) produced a handbook on windthrow of trees addressing forest and open grown trees. The handbook covers what is known about windthrow susceptibility based on general characteristics of tree structure, soil conditions, and existing environments. The guide provides a number of illustrations of relative susceptibility to windthrow based on tree size, crown and root characteristics, and surrounding elements of the environment.

Slope Effects

The topic of root systems of trees growing on slopes has received some attention in recent years. Most of that attention has been related to the ability of tree roots to stabilize soils and prevent or reduce landslides. Some attention has been given to how rooting affects the tree's ability to remain upright under severe conditions. All of this information may be useful in understanding how the roots of trees growing on levees and close to levee toes may respond to levee structure. It may also provide insight into the potential effect tree roots have on the structural integrity of levees.

A study of Douglas-fir root systems across a variety of ages (10, 25, 40, and 55 years) on sloping soils revealed differences in symmetry upslope and down slope from the trees (McMinn 1963). McMinn found down-slope roots were fewer in number and descended rapidly, ending abruptly in deeper soils. The upslope roots were more numerous and traversed great distances while maintaining a positive upslope angle. Coutts (2004) summarized much of the available literature on tree effects on sloping soils and their integrity. The study covered many aspects of tree roots, including architecture, topology, tensile strength, soils, and hydrological interactions on sloping sites. A "Slopes Decision Support System" was developed for use in assessing and using trees to rectify slope instability problems. Coutts cautioned that trees tolerant to one type of stress might be susceptible to other types of stress. Coutts generalized that trees with wide-spreading, deep root systems tend to resist windthrow the best; however, he also noted that well-anchored species on one soil may be less so on other soils. He also warned that although tree root systems tend to bind soil together reducing the chance of erosion and landslides, trees are also subject to overturning and, therefore, can have negative effects; these effects are often critical factors in landslides (and presumably, it may follow that overturning trees may exacerbate the loss of levee integrity).

Di Iorio et al. (2005) investigated the root architecture of pubescent oak (*Quercus pubescens)* growing on sloping soils. They compared cross-sectional root area and root volume and found root volume to be more suitable for assessing root bending and root taper. The degree of slope affected root volume of different orders of root branching. Trees on sloping soils tended to have a clustering of first- and second-order roots in the upslope direction. When slopes were very steep, even the taproot was positively correlated to the magnitude of the first-order root symmetry. This adaptive growth improved tree stability on steep slopes by counteracting the turning moment induced by self-loading forces under these conditions. Nicoll et al. (2006a) evaluated the root system architecture of 40-year-old Sitka spruce trees (*Picea sitchenis*) growing on horizontal and sloping (26°) sites in western Scotland. Trees growing on sloping sites had asymmetric roots with the majority of the root system mass oriented towards prevailing wind and upslope. The largest areas devoid of roots were downslope. Trees on horizontal sites had symmetric root distribution with no significant clustering. Nicoll et al. (2006a) point out the conflicts in the literature on root orientation with respect to slopes. On shallow sloping soils some studies have reported the opposite trends, where the majority of roots appear on the leeward sides of stems. Some interaction between wind and slope is likely.

Nicoll et al. (2006b) performed a meta-analysis on the relationships root anchorage to species, soil groups, and root depth classes on several conifer species in the British Isles. Grand fir (*Abies grandis)* was the best anchored on deep, well-drained mineral soils; however, Sitka spruce (*Picea sitchensis)* was much better anchored than lodgepole pine (*Pinus cortorta*), the only other species found on deep, peaty soils. Most species were shallow rooted on gleyed, mineral soils, but grand fir had the poorest anchorage. They indicated that prevailing winds and wind speeds interact with other properties to increase root anchorage.

Nilaweera and Nutalaya (1999) evaluated the effects of root diameters, root length, and root volumes on tensile strength and pull-out resistance for trees relative to soil stabilization in mountainous areas of Thailand. Root tensile strength was found to decrease with increasing root diameter, while pull-out resistance increased with increasing length and rooting depth. Root volume was not closely related to either, because length and diameter relationships varied with volume. Actual pull-out resistance was affected by a combination of root-related factors and was not solely related to root depth. For instance, white thingan (*Hopea odorata)*, largeleaf rosemallow (*Hibiscus manrophyllus)*, Yang tree (*Dipterocarpus alatus)*, and weeping fig (*Ficus benjamina)* had mean root depths of 30.4, 25.7, 21.4, and 16.4 inches (78, 66, 55, and 42 cm), respectively, but pull-out forces were 1.9, 4.0, 1.8, and 4.6 kN, respectively. Both root length and the number of roots were important.

Watson et al. (1999) measured the effects of deforestation-related root decay on the stability of slopes. They indicated that some literature shows inadequate root reinforcement of soil stability for up to 6 years following harvest. They chose sites in New Zealand that had been cleared of the original forest for pasture but were then converted to plantations of Monterey pine (*Pinus radiata*) and knauka (*Kunzea ericoides*). Both species are deep rooted (10.1 ft and 7.2 ft, respectively), some to 32.8 ft, and have extensive root systems (radial extent averaging 29.5 ft and 11.8 ft, respectively). Soil stability after clearfelling was related to the rate of live root loss and the decrease in root strength. The root strength of kanuka actually increased during the first year after tree harvest before beginning to decline, while the root strength of radiata pine began to decrease almost immediately. Therefore, slopes growing under radiata pine were more rapidly susceptible to failure. Recovery rate was therefore delayed even after new radiata pine trees were planted. Species-site interactions are important. Zeimer (1981) evaluated root decay after harvesting in the Pacific Rim. Zeimer concluded that forest harvest and the resulting root decay left slopes susceptible to failure. Studied forests contained only one-third of the original root biomass just 3 years after harvest. He suggested that little information existed on the rates of root decay among species and how this was affected by trees size and growing conditions. Zeimer reported that seven years after harvest, nearly all roots less than 0.1 inches (2 mm) diameter were missing and only 30% of those less than 0.7 inches (17 mm) were still present.

Levees and Tree Roots

The policies regarding levee upkeep and security in south Louisiana and most other places in the U.S. often lead to exclusion of trees from the levee proper. The reasons given for excluding trees from levees are many, but include (1) provisions for ready, unobstructed inspection, (2) the unrestricted access and ability to make repairs at critical times, (3) the potential impacts of overturned trees on levee stability, and (4) the potential of piping or root channel development caused by decay of large tree roots. Although studies of trees and tree root effects on levees have undoubtedly been done (at least informally), the scientific, peer-review literature is almost devoid of such papers. A few papers from the "grey" literature (not peer reviewed) are included here, but they are much more difficult to locate and evaluate.

One of the major objectives of this literature synthesis was to explore literature topics relevant to how tree roots might behave in levees and along outfall canals. The subjects covered earlier in this synthesis provide information that is useful in understanding the behavior of roots and root extent under conditions somewhat similar to that which exists on levees, but there could be significant differences. Trees growing on levees probably respond in a very similar manner to the root behavior discussed previously, however, trees growing at the levee toe have somewhat different environments and potential responses (than those growing on levees). At least two different situations exist for trees growing near the toe of levees. First, those trees that were in place at the time of levee construction may have had existing roots in the area of levee construction (initial roots below the levee proper) and knowledge of what happens to those roots over time is severely lacking. Second, trees that were planted in or invaded the area below the toe of the levee after levee construction (no initial roots below the levee proper) may respond differently than trees planted on or occurring naturally on slopes. Roots of trees growing adjacent to slopes have not been widely studied (this may be a fruitful area of exploration, helpful in understanding tree root behavior in levees).

One study of the root effects on levees along the Sacramento River in California (REMRa) included an evaluation of five tree species and associated shrubs (Gray et al. 1991). Trenching under the canopy of trees and mapping of the root systems allowed analysis of measured root traits. Roots of valley oak (*Quercus lobata*) and shrub willow (*Salix hendsiana*) dominated the root area index (RAR) in the root zone from 4 to 12 inches deep. Elderberry (*Sambucus mexicana*) had the highest RAR at 28 inches, but the oaks and willows generally dominated the root zone as a whole. Dead oaks existed on the levees and even ten years after their death these trees still had tap roots at 4.6 ft (1.4 m) deep, and lateral roots less than 0.33 ft (0.1 m) deep still existed. All areas containing decayed roots were filled with sand (no open root channels). Gray et al. cautioned that sinker roots and roots vertically oriented may not be characterized and accounted for in vertical wall profiles. Although they thought vertical wall profiles were the best overall technique for assessing root behavior, they suggested more research using excavation of whole root systems was needed to provide appropriate information on vertical roots. Soil voids were mostly due to ground squirrel and insect activity in the sandy levee soils studied. No voids clearly attributable to plant roots were observed. Small voids were filled quickly with sediment during floods. Large roots decay slowly and replacement by sediment or new roots is compensatory. Gray et al. found that plant roots reinforced levee soils and significantly increased soil shear strength. Grass roots provided the best reinforcement near the surface, but shrubs (e.g. elderberry) and trees had deeper roots, providing reinforcement of shear strength deeper in the soil, protecting soils deeper seated failures. Low growing shrubs and trees offer protection from soil shear while not adding significantly to chance of windthrow and related problems. These findings were restricted to the sandy soils in the region of research. Gray et al. suggested expanding the research to other soils, regions, and species.

Shields and Gray (1992) investigated dominant trees along the levee slope of the Sacramento River in California. They excavated trenches near dominant trees of valley oaks (*Quercus lobata)* and cottonwood (*Populus fremontii)*. They found voids caused by burrowing animals and insects at all depths, but found no voids caused by roots. The number of roots per square meter of trench wall area (root density) declined logarithmically with increasing root diameter. The root density for roots greater than 0.8 inches (2 cm) diameter was less than 10 for elderberry and less than 1 within woody driplines. A dead oak stump was characterized as having a large tap root of 0.65 to 1.3 ft (0.2 to 0.4 m) in diameter and a series of spreading lateral roots at depths of 1.9 to 3.9 ft (0.6 to 1.2 m). Most of the roots angled sharply downward. Shields and Gray (1992) indicated that on these older, steeper, sandy levee systems, the tree roots considerably enhanced the safety factor by as much as 16-fold. The greatest effect of roots on the safety factor was near the surface. Roots of these trees were found to reinforce the levee soils and increase the shear resistance. Their results suggested that allowing woody shrubs and small trees to establish on levees would provide environmental benefits, enhance structural integrity, and would not produce hazards commonly associated with large trees and windthrow.

Wallace et al. (1994) reported on the potential armoring of levees with woody vegetation. This report was the result of reviews of the flood effects on levees in the Midwest which occurred during the summer of 1993. They used both published and unpublished information and aerial survey reports of levee conditions and damage following this flood. Areas of levees with 65.6 to 328 ft (20 to 100 meters) of tree corridors revealed only a single break while those with no tree cover had multiple breaks. They indicated that over 2000 breaks occurred in secondary levees in Missouri, but surveys of the damage indicated that levee sections buffered by forests were protected and had fewer breaks than those levee sections not near forests. Levee sections with willow or other forests between the river and the levee showed few signs of injury from scouring or wave action. According to the review, areas with woody vegetation reduced flow velocity by increasing drag forces. Wallace et al. discussed some potential design and management strategies for protecting levees with trees on the river side.

Several papers at the 2007 Sacramento "Vegetation Challenge Symposium" offer additional insight into the influence of trees and other vegetation on levees. Berry (2007) provided an introduction to basic tree root behavior and some of the anomalies that occur. She reported on a recent and ongoing investigation of tree roots in the Central Valley of California. She contrasted the root character of cottonwood, Douglas-fir, and valley oaks. Her work in the study at Mayhew in Sacramento related to three mature oaks on which root wall profile mapping was performed. An L-shaped trench 48-ft long and 4-ft deep about 14 ft from the trunk of the tree was excavated. Root locations were dotted on acetate sheet and sizes were recorded. Roots were not found when soil bulk densities exceeded 1.63 in a sandy loam soil. Most roots measured with the root wall profile technique were in the upper 2 ft of soil. Few roots were found between 2 and 4 ft of depth. Ground penetrating radar was used to search for roots deeper than 4 feet. Initial data indicated large roots, those greater than 1 inch in diameter, occurred at depths of 4 to 6 feet. The author suggested some roots may be growing beneath the levee. One actual sample, below 4 feet, revealed roots in the 4 to 6 foot depth confirming the initial GPR images.

Peterson (2007, "Vegetation Challenge Symposium") gave a presentation dealing primarily with tree falls and those factors influencing the uprooting or breakage of trees. The presentation reviewed several factors contributing to wind damage and windthrow including hurricanes, tornados, coastal winds, tree and stand characteristics, and site characteristics. Peterson mentioned the paucity of information related to the effects of wind on trees occupying levees and the species in review at the symposium. The presentation contained information on drag forces of crowns relative to wind and the differences produced by species, tree size, and wind speed. The crown deformation effects during storms were also mentioned. The biomechanics of breakage versus bending and windthrow were discussed. Site characteristics and topography also affected forces on trees. Soil saturation and hardpans within soils limit the extent of rooting and therefore increase windthrow risk in some sites.

Shields (2007, "Vegetation Challenge Symposium") reported on studies he had performed in the 1980s and early 1990s on six sites along the Sacramento River. A portion of this work is reported above. Soils, vegetation, root size, and root distribution were outlined relative to stability of levees. Data were used to conduct a slope stability evaluation. Root area ratios (RAR) were used to discuss root distributions within the soil profiles and make comparisons among different types of vegetation assuming similar relationships between RAR and soil cohesion that others found in laboratory tests. Using this relationship both an infinite slope stability analysis and a circular arc analysis of slope failure were performed. Vegetation increased levee stability. Models predicted levee failure would occur when vegetation was absent from the levees. Deeper rooted plants such as trees and shrubs produced better stability under the circular arc conditions. Roots increased soil cohesion only 50% but had major effect on the safety factor. Aerial photographs before and after a 1986 flood were used to confirm predictions. One acknowledged limitation is that Shields and coworkers did not consider windthrow or seepage in their models of levee slope failure. Comparing vegetated and unvegetated revetment areas they found that revetments with vegetation had less damage than those without vegetation.

Remote Sensing

Ground penetrating radar is the most frequently mentioned technique for sampling of root size (diameter) and root distribution without digging. A few papers with relevance to this method of assessing tree root distributions are summarized here (also see annotated bibliography), however, the literature generally suggests that this technique will not be extremely useful in south Louisiana. Maps of suitability are available from NRCS at ftp://ftp-fc.sc.egov.usda.gov/NGDC/ssatlas/gpr/la_e.pdf

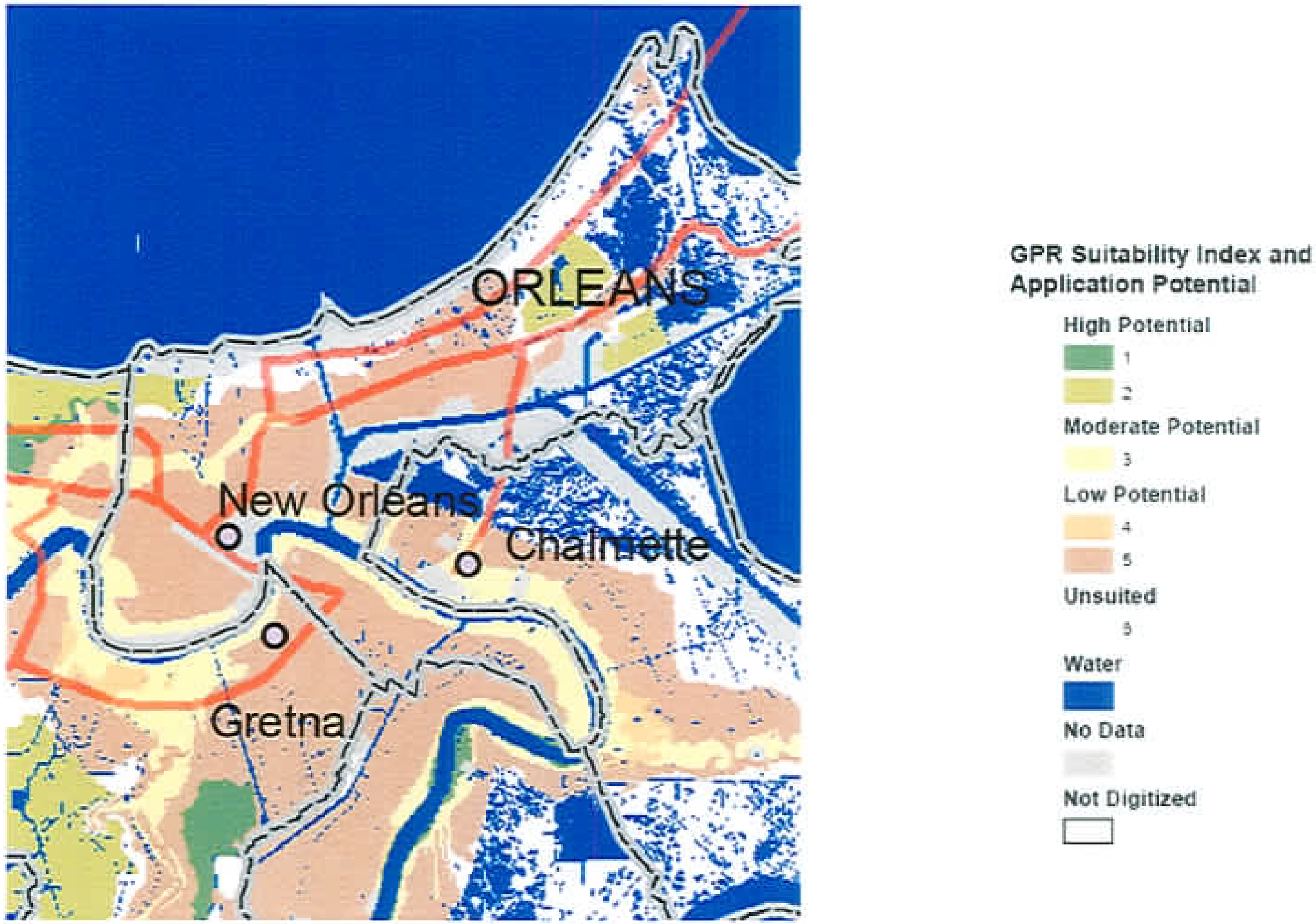


Figure 1. Illustrates suitability of areas for the use of Ground penetrating radar (GPR). Areas of darker beige indicate the areas of least suitability for use of GPR. (NRSC).

Root system detection suitability would be least viable in wet, clay soils and soils with obstructions or inclusions and best in sandy and dry soils. Included items in levees are a problem. In soils with high water content, only the first 0.5 m of depth would be useful.

Butnor et al. (2001) tested ground penetrating radar (GPR) to examine root distributions in several forested areas of the southeastern U.S. They found that GPR, when used correctly and scanned perpendicular to roots, was reliable with an r^2 of 0.55, but that it was not adequate for clay soils, excessively wet soils, and soils with obstructions of various sizes (such as found in the levees of our current study). Uneven surface soils presented severe problems. They also indicated that water tables severely distort root signals. Live roots were detectable, but dead roots were often undetected even at much larger diameters. In clay soils, the inclusions of coarse fragments and rocks were often mistaken for roots. Butnor et al. (2003) used GPR to evaluate root systems of young loblolly (*Pinus taeda)* in sandy loam soils that were well drained to excessively well drained. They indicated that under those ideal conditions they were able to accurately assess root system distribution and root volumes. However, even in these ideal conditions they did have problems. Calibration was required for each set of soil conditions (GPR would not work well in variable soils on outfall canals). Fertilization, even on the uniform soils in their study lead to detection problems because of the increase in root density. Scanning depth on these plots was reduced to the upper 11.7 inches (30 cm) even in this ideal sandy loam soil. Four hours were needed to scan just 1000 linear feet of soil in a narrow band and scanning had to occur on an even surface with no more than pine needles as a disruption. Hruska et al. (1999) scanned root systems of sessile oak (*Quercus petraea)* on loamy soils. For a scan to a depth of 6.5 ft for a 19.5 ft by 19.5 ft scan (2 m for a 6 m by 6-m scan) in a 0.8 ft by 0.8 ft (0.25 m by 0.25 m) segment required 6 hours of scanning time and 30 hours of processing time. Complicating factors included coarse root interference and stones. Barton and Montagu (2004) describe the conditions and restrictions for using GPR for the purpose of tree root detection. According to their description, only scans perpendicular to the roots give quality data; high clay, high water content, and high salinity attenuate the signals rapidly, so detection is limited to near the surface (depths of less than 3.3 feet). Some signal conditioning and waveform analysis can be used for correction and could produce good results to 4.9 ft (1.5 m) when roots were scanned at right angles in uniform dry sandy soils.

Nadezdina and Cermak (2003) reviewed several root measurement techniques. They indicated that GPR coverage of a 322.9 ft^2 (30 m^2) area required between 6,000 and 10,000 images for a tree; additionally, sticks and rocks needed to be removed. They also reviewed the use of differential electrical conductivity for the assessment of root surface conducting area. However, with this technique, root distribution and root size are not available. In addition extensive sampling is needed.

Root Barriers

Protection of engineered structures, such as sidewalks, pavement, buildings, and even levees is needed when the desire is to keep valuable or historic trees from conflicting with these structures. Tree root barriers have been manufactured for such use for a number of years. In most cases, the barriers only need to restrict root egress at shallow depths (not the case for levees). Little scientific literature exists on the applicability of root barriers for deep growing roots.

Coder (1998), in a review of applications for root barriers, suggested flaws in engineering cause most of the damage frequently attributed to trees. . Still, tree root system conflicts with structures are inevitable and may sometimes need to be resolved by the use of root barriers. Coder's main recommendation was to avoid tree placement or establishment near sensitive structures. He mentions the major downside of root barriers as being the ability of tree roots to escape from the barriers by growing over the top, under the bottom, or through gaps (breaks or tears) in the barrier caused by faulting or careless installation. Coder reviews the strengths and weaknesses of several types of barriers including traps, deflectors, and inhibitors. Randrup et al. (2001) provide a review of the little scientific literature available on root barriers. They compare some types, and include limited information on cost, repair frequency, and other information. However, the review is limited and probably of little benefit in decisions regarding which barriers are capable of preventing root growth into levees.

Peper (1998) tested three commercial barriers, Deep Root, TreeRoot, and Vespro for the containment of white mulberry roots. He found that 11.7-inch deep (30 cm) root barriers reduced surface root biomass outside the barriers, but they did not reduce root diameters. He also found that 23.4-inch deep (60 cm) barriers reduced both root biomass and root diameters outside the barrier for the duration of the study. Roots were forced to grow downward for the depth of the barrier in all three types tested. Peper and Mori (1999) tested barrier effectiveness for Chinese hackberry (*Celtis sinensis)*. All tested barriers were effective to the barrier depth, but barriers with vertical ribs prevented or reduced circling of roots (a negative) within the barrier. Roots circumventing the lower level of the barrier grew upwards and then resumed growth similar to roots in control plants without barriers. Pittenger and Hodel (1999) found similar upward growth of tree roots escaping below barriers for sweetgum (*Liquidambar styraciflua)* and Indian laurel (*Ficus nitida)*. Smiley (2005) tested the effectiveness of five types of barriers on 2-year root growth of 1.5-inch diameter willow oak (*Quercus phellos)*. Barriers were installed 2 ft from the tree stems to a depth of 18 inches. After two years, no roots had penetrated barriers in any of the barrier systems. There were no differences in roots within the barrier zones, except for the control trees, which had more roots. However, chemically treated barriers were able to reduce overall growth near the barriers. Roots systems were similar below the barriers.

Wilson and Lester (2002) tested trench inserts (root barriers) as a means of reducing or preventing the spread of oak wilt through root contact among mature live oak *(Quercus virginiana*) roots. Barriers or trench inserts were tested for a period of 7 years. Linear trenches 4.9 ft (1.5 m) deep were lined with trench insert materials. Four trench insert materials were tested, including water permeable Typar polypropylene spunbonded fabric of a 4 ounce weight; water-permeable Biobarrier or Typar with trifluralin-impregnated 0.4 in (10 mm) diameter controlled-release pellets bonded to polypropylene fabric; and water-impermeable polyethylene Rufco Geomembrane liners of both 20 and 30-mil thickness. Untrenched trees were used as controls and also compared to trees with unlined trenches and fungicides added. Infections occurred within the first year in many of the untrenched trees, but infections were not evident until year three in any of the trees within treatments lined with trench barriers. The breakouts only occurred in trenched trees with the thinner water-impermeable Geomembrane 20 mil barrier. No breakout occurred in any of the other barrier treatments through year five. Over the course of the seven year study no breakouts occurred in the water-permeable Biobarrier, Typar, or water-impermeable Geomembrane 30-mil trench inserts. No root penetrations occurred in any of the treatments with trench inserts. Root contacts with the barriers did occur in all but the Biobarrier lined trenches that had fungicides incorporated. All breakouts were associated with roots that either grew over or under the trench inserts. Such breakouts were only noted in the water-impermeable trench liners. Roots in the water-permeable trench liners tended to branch prolifically rather than be seriously diverted as in the water-impermeable lined trenches. The chemically treated water-impermeable liner inhibited root tip growth as roots approached the liners. The Typar water-permeable liners were about 70% to 80% less expensive than the chemically treated, water-permeable Biobarrier liner. The Typar barrier was also available in several thicknesses. This paper provides manufacturer information for barrier materials that may be relevant to certain metropolitan levee situations. Research is needed on the performance of such materials in levee situations where soil erosion may lead to root overtopping of barriers over time. Such overtopping could be prevented by proper engineering and maintenance. The very long-term durability of these materials is uncertain but promising.

Literature Cited

Refer to Annotated Bibliography (**Appendix 5**) for all citations in this literature synthesis.

Phase 2

Data Collection Protocol

Initial Exploration

In the initial stages of the project, the Team worked cooperatively with the New Orleans District's tree removal contractor (Three Fold Consultants, LLC) to visually evaluate the possibility of coordinating some of our root system measurements with their tree removal operations along the London Avenue Outfall Levee. We were unable to collect actual measurements from this work and changed our approach for three primary reasons: 1) the method of tree removal used destroyed sections of the trees and root systems such that measurement of root size, root location, and tree size could not be evaluated with necessary accuracy or repeatability; 2) the time needed for our measurements would have prevented Three Fold from completing their work within their allotted time and budget constraints; and 3) the operating conditions would have been unsafe for our personnel to work. Three Fold was the most cooperative contractor we spoke with and they did aid us considerably in early exploration of root depth, especially with deep roots. They also aided in the initial investigation of species differences by providing some deep excavations of roots of several large trees.

Initial data collection involved the development of an initial protocol for root system measurement. In lieu of coordinated measurements, we decided to have Three Fold excavate exploratory trenches for selected sample trees of sycamore (*Plantanus occidentalis*), baldcypress (*Taxodium disthicum*), live oak (*Quercus virginiana*), water oak (*Quercus nigra*), pecan (*Carya illinoinsis*), and sugarberry (*Celtis laevigata*) to investigate the general characteristics and distribution of these root systems. This initial exploration of root system was done to a depth considered safe based on the soil characteristics as revealed during excavation (e.g., integrity of the trench faces, absence of water in the trenches or along their faces, etc). Generally the trenches were 7 to 8-ft deep and ranged from 10 to 20 ft in length. Personnel were not allowed to enter the trenches once they reached a depth of 4 ft. Water oak and sugarberry had the shallowest roots in the trenches and levee sections explored by this method. Most of the observable roots for these two species, greater than 0.5 inches in diameter, were contained within the upper 12 inches of the profile with some extending to a depth of 3 to 3.5 ft. The majority of roots of the other species were also contained within the same soil depth, but a small number of large roots, 2 to 6 inches in diameter or more, were observed at greater depths. The deepest roots were observed in the selected baldcypress and live oak trees and these occurred at the maximum excavated depths of ~ 7.5 to 8.0 ft. These were large roots estimated to exceed 6 inches in diameter and projecting downward at the face of the trench. Each of these deep large roots and similar large roots in sycamore excavation trenches occurred at some distance from the tree (20 to 30 ft). Time constraints and the gravel road along the west side of the

London Avenue Outfall Canal did not allow us to explore the entire length of the system. Safety precautions did not allow us to excavate deeper. Similar observations of large diameter roots were made of the selected pecan but at a distance of 15 ft from the tree. The exact nature and distribution of these large penetrating deep roots should be explored on a more detailed basis. Roots were noted to be larger in diameter in areas of blue clay soils for baldcypress, live oak, and sycamore. This was not a formal analysis of tree roots, but simply *ad hoc* observations that lead us to question the sufficiency of knowledge to be gained from our formal measurement trenches that were restricted to a depth of 3.5 ft.

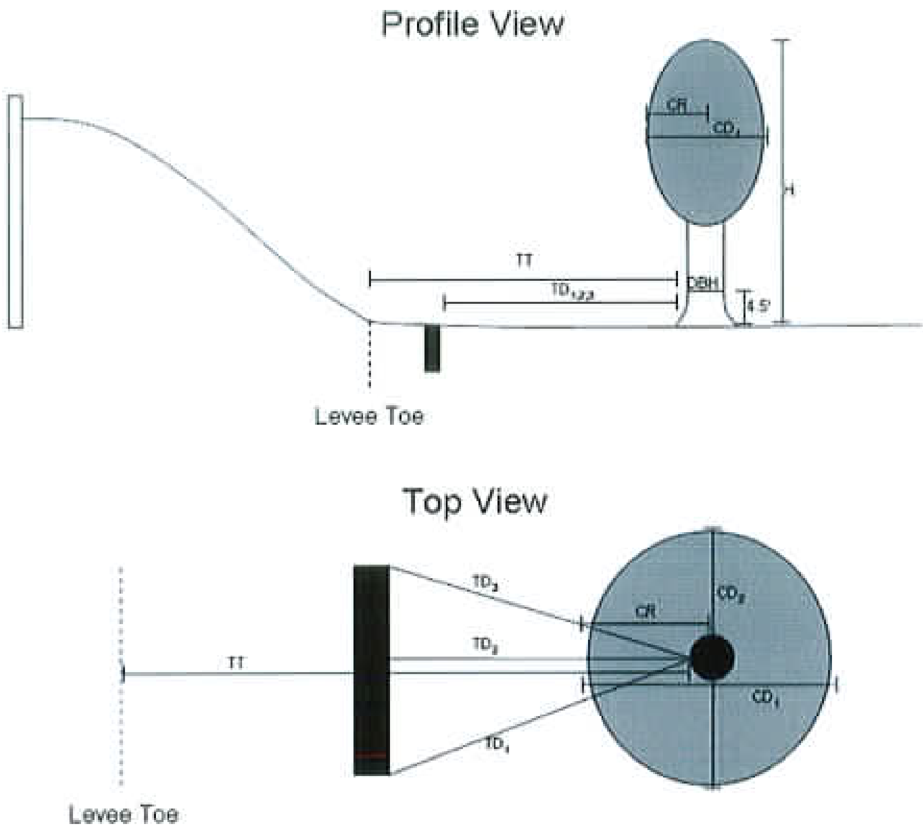
An initial protocol for data collection included scouting potential trees for measurement to fit the size and species categories in our proposal; flagging or otherwise marking these trees; and recording latitude and longitude via GPS and initial size and distance for each marked tree. Each flagged tree was later evaluated as to its value to the project. If selected, trenching was performed at preset distances from the tree for root measurements. Once a set of trees was selected for initial root measurements, we explored several procedural methods of pit excavation, trench wall marking, and root counting. We also explored different methods for characterizing the soil medium. Initial trenches did not include all measurements. Some added measurements and changes in data sheets (see Appendix 1: sample data sheet) were determined to be valuable or necessary, and changes were made as we encountered additional complexities and attributes of trees, levee sections, soils, and logistics of measurement.

Protocol

The adopted protocol for current root and tree measurements along the outfall canals in New Orleans are as follows (see sample data sheet, Appendix 1):

- Maps, photographs, and other documentation supplied by the Corp were used to aid in tree selections and field visits added confirmation to some of these selections. However, on-site field selection proved to be more efficient and was used for selecting most trees. Selected measurement trees and stumps were clearly marked with various combinations of temporary flags and brightly colored paint for the field measurement crew and other crews such as contractors, the Corp, etc.
- The general tree measurements to be taken were modified as needed. Some measurements could not be made on stumps of trees cut prior to sampling.. Therefore, not all data sheets include all measurements. General measurements include tree location (latitude and longitude), diameter at breast height (4.5 ft) (or specified height in the case of stumps and trees with abnormalities at 4.5 ft), tree height, and species (Figure 2). Tree-crown radius parallel to the measurement trench and crown radii in that direction and approximately normal to that direction were measured. Height and crown measurements are not available for stumps. Other measurements include distance from tree to toe of levee slope (Corp line

when marked) and distance from tree to the face of each successive trench wall if present.



TT:	Distance from the tree to the toe of the levee
TD1,2,3:	Distances from the tree to the corners and center of each trench
CR:	Crown radius, measured perpendicular to the trench on the half of the tree closest to the trench
CD1,2:	Crown diameters, measured both perpendicular and parallel to the trench
H:	Total tree height
DBH:	Diameter at breast height (4.5 feet from the ground)

Figure 2. Idealized diagram depicting typical measurements taken for trees studied along levees and floodwalls in the New Orleans area. Black boxes represent trenches and grey circles represent sample tree crowns. Not all measurements depicted could be taken on all trees, as some were felled and removed prior to measurement. Stump diameters were taken for trees felled prior to tree measurements.

- Generally, the first trench was at least 9 ft from the tree and successive trenches were placed at approximately 6 ft intervals away from the front wall of the previous trench (Figure 3, see Appendix 1 for additional examples). Additional trenches were added when roots in the current trench exceeded 0.5 inches in diameter. Reasons for discontinuing successive trenches were safety, working conditions, and insufficient distance from the trench to the levee wall. Some early trenching was discontinued because of conflicts with contract work for root and tree removal.

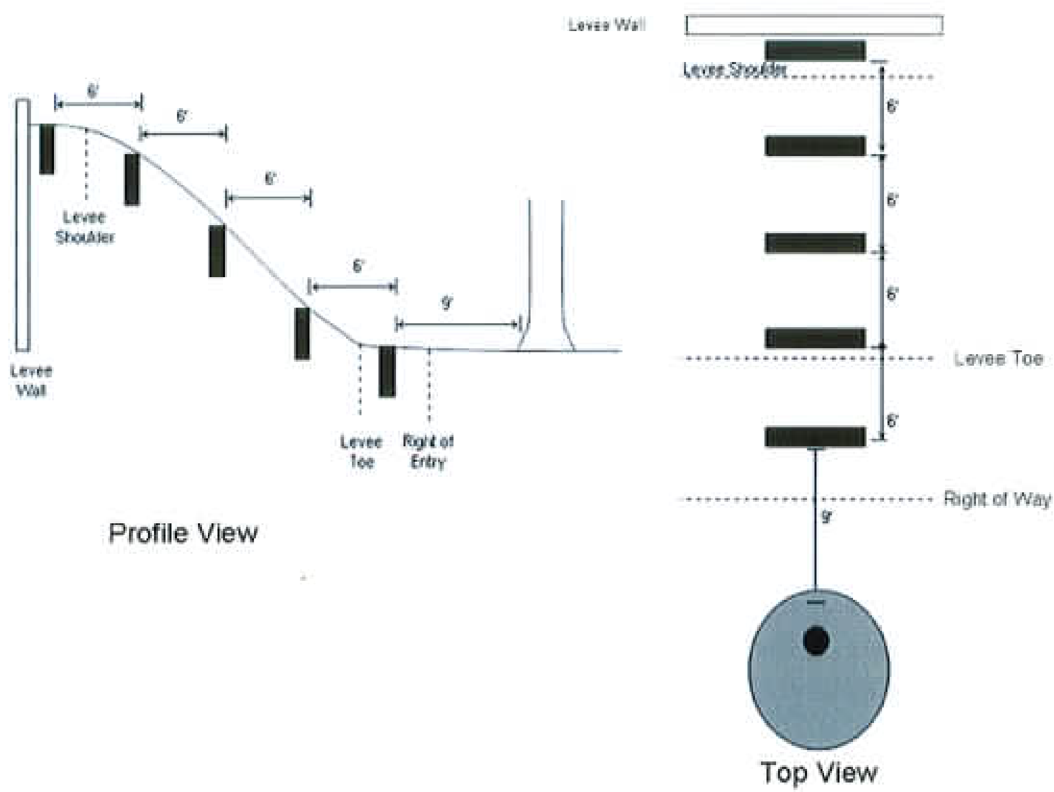


Figure 3. Idealized trenching diagram for root wall profile trenches used in this study. The black boxes represent an idealized trench placement along the levees/floodwalls in the New Orleans area. The first root profile trench cut for each tree (grey circle) generally was placed at least 9 ft from the base of a tree in the direction of the levee wall and parallel to it. Successive root profile trenches were spaced approximately 6 ft closer to the levee wall than each preceding trench. Successive trenches were excavated until there were no roots greater than 0.5 inches in diameter or conditions did not permit additional trenches (see text). Distance from tree to the first trench were varied to obtain a range of distances, species, and tree diameters.

- Trench and root related measurements (included descriptions, or samples associated with each measurement trench): Trench measurement zones extended from the soil surface to a depth of 3 ft and horizontally for 10-ft (at each trench location. The trench was roughly centered so that 5 ft of measurement wall occurred either direction from the approximate projected center of the measurement tree stem). The measured portion of each trench was divided into 1-ft vertical increments and 2-ft horizontal increments (some early work used 1-ft horizontal increments, but data were later combined into 2-ft increments) for a total of 15 root-measurement cells (Figure 4). Cell boundaries are delineated by temporarily placing a colored strand of rope or flagging at each 1-ft depth interval and cells across the measurement wall were delineated by vertical placement of colored flagging in strips at each 2-ft mark horizontally along the trench face.

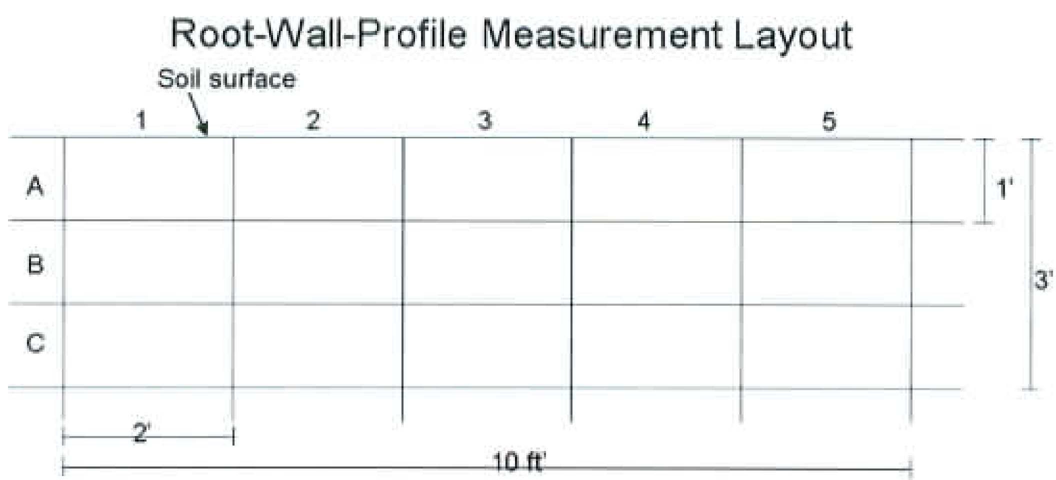


Figure 4. Idealized root-wall profile layout containing fifteen measurement cells. All roots greater than 0.5 inches in diameter were tallied within each cell.

- Measurements within the profile included the following:
    - soil texture by feel in each 1-ft layer with descriptions of uniformity and inclusions or other buried objects
    - soil strength measured with a pin penetrometer for each cell
    - roots were counted in each of three diameter classes (0.5 to 0.99; 1.0 to 1.49; and 1.5 to 2.0 inches) within each designated measurement cell
    - roots with larger diameters are measured with calipers and diameters were recorded
    - photographs were taken at each trench and often included both tree and trench views (See below)
    - All protocols were subject to modification as needed. Modifications generally included additional information and added measurements as different needs and conditions arose.

Photographic Documentation

For most trees after the initial data collection trials (protocol development), soil trench photographs were taken to record the general nature of the root systems. Some photographs are taken of trees as well (in a number of cases the trees were cut by Corp tree removal contractors before tree and root measurements had begun). Many measurement trees were documented with four pictures, one of the tree or stump, and three of the sample wall of the trenches. Photographs were labeled to correspond to trench identification code data (included on accompanying CD). Below are sample photographs depicting trees and trenches along the outfall canals in New Orleans.

Typical water oak, *Quercus nigra*, along the west side of the London Avenue Outfall Canal.

Early trench work for root measurements depicting initial protocol development.

Large root at ~ 7.5 ft depth in trench exploration work with Three Fold Consultants.

Root measurement cell delineation used to spatially segregate measurements of roots, soil strength, soil texture, and soil sample locations.

Compaction Quality Assurance

In order to verify standard compaction, JESCO proposed running In-Place Density Tests at various trench locations. JESCO tested the recompacted fill material in accordance with ASTM D 2922 (Nuclear Method). As described in the original workplan, One (1) trench was tested for every twenty (20) trenches excavated with the exception of the Lakefront and Mississippi River Abandoned Levee Sections. Regarding the Lakefront Levee, the New Orleans District requested a compaction test be performed on each observation trench developed directly in the Lakefront Levee. Additionally, the New Orleans District stated trenches did not require tests that were located completely outside the levee structure. Compaction tests were not performed at the abandon levee sections located near the Mississippi River Levee Sections in Bayou Goula and Cannonburg, LA.

Selected soil samples were collected from each investigation location and submitted to Beta Testing & Inspection, LLC (geotechnical laboratory) for analysis of Moisture Content (ASTM D2216), and Standard Proctor (ASTM D698A). The Standard Proctor and Nuclear Density results are shown as Appendix 7. The tested trenches were required to meet or exceed 90% compaction. All trenches tested met or exceeded the required 90% compaction.

The following information shows the number of trenches sampled during the study:

London Avenue Canal – 4 trenches tested, Passed

Orleans Canal – 2 trenches tested, Passed

Lakefront Levee – 26 trenches tested, Passed

17th Street Canal – 7 trenches tested, Passed

Mississippi River Levee Sect. 5155, 5070, & 4990 – Abandoned levees, No testing required

Mississippi River Levee Sect. 5595 – Abandoned levees, No testing required

Total # of Tests – Total of 39 trenches sampled (Total of 217 trenches in study)

Phase 2

Data Collection Protocol

Initial Exploration

In the initial stages of the project, the Team worked cooperatively with the New Orleans District's tree removal contractor (Three Fold Consultants, LLC) to visually evaluate the possibility of coordinating some of our root system measurements with their tree removal operations along the London Avenue Outfall Levee. We were unable to collect actual measurements from this work and changed our approach for three primary reasons: 1) the method of tree removal used destroyed sections of the trees and root systems such that measurement of root size, root location, and tree size could not be evaluated with necessary accuracy or repeatability; 2) the time needed for our measurements would have prevented Three Fold from completing their work within their allotted time and budget constraints; and 3) the operating conditions would have been unsafe for our personnel to work. Three Fold was the most cooperative contractor we spoke with and they did aid us considerably in early exploration of root depth, especially with deep roots. They also aided in the initial investigation of species differences by providing some deep excavations of roots of several large trees.

Initial data collection involved the development of an initial protocol for root system measurement. In lieu of coordinated measurements, we decided to have Three Fold excavate exploratory trenches for selected sample trees of sycamore (*Plantanus occidentalis*), baldcypress (*Taxodium disthicum*), live oak (*Quercus virginiana*), water oak (*Quercus nigra*), pecan (*Carya illinoinsis*), and sugarberry (*Celtis laevigata*) to investigate the general characteristics and distribution of these root systems. This initial exploration of root system was done to a depth considered safe based on the soil characteristics as revealed during excavation (e.g., integrity of the trench faces, absence of water in the trenches or along their faces, etc). Generally the trenches were 7 to 8-ft deep and ranged from 10 to 20 ft in length. Personnel were not allowed to enter the trenches once they reached a depth of 4 ft. Water oak and sugarberry had the shallowest roots in the trenches and levee sections explored by this method. Most of the observable roots for these two species, greater than 0.5 inches in diameter, were contained within the upper 12 inches of the profile with some extending to a depth of 3 to 3.5 ft. The majority of roots of the other species were also contained within the same soil depth, but a small number of large roots, 2 to 6 inches in diameter or more, were observed at greater depths. The deepest roots were observed in the selected baldcypress and live oak trees and these occurred at the maximum excavated depths of ~ 7.5 to 8.0 ft. These were large roots estimated to exceed 6 inches in diameter and projecting downward at the face of the trench. Each of these deep large roots and similar large roots in sycamore excavation trenches occurred at some distance from the tree (20 to 30 ft). Time constraints and the gravel road along the west side of the

London Avenue Outfall Canal did not allow us to explore the entire length of the system. Safety precautions did not allow us to excavate deeper. Similar observations of large diameter roots were made of the selected pecan but at a distance of 15 ft from the tree. The exact nature and distribution of these large penetrating deep roots should be explored on a more detailed basis. Roots were noted to be larger in diameter in areas of blue clay soils for baldcypress, live oak, and sycamore. This was not a formal analysis of tree roots, but simply *ad hoc* observations that lead us to question the sufficiency of knowledge to be gained from our formal measurement trenches that were restricted to a depth of 3.5 ft.

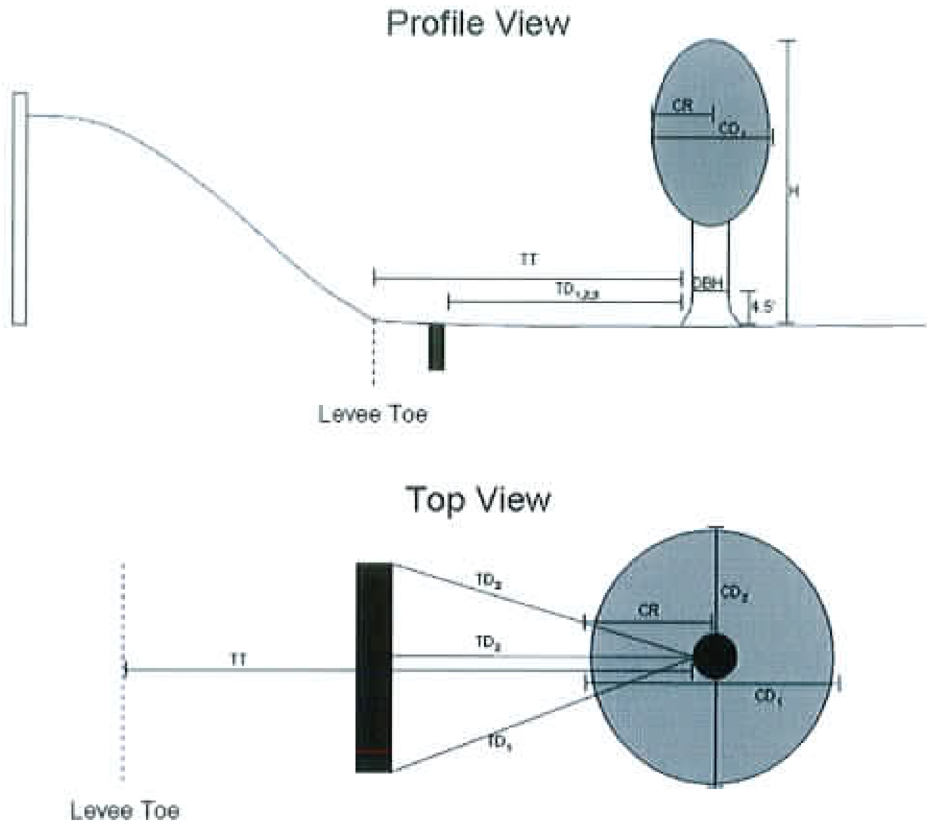
An initial protocol for data collection included scouting potential trees for measurement to fit the size and species categories in our proposal; flagging or otherwise marking these trees; and recording latitude and longitude via GPS and initial size and distance for each marked tree. Each flagged tree was later evaluated as to its value to the project. If selected, trenching was performed at preset distances from the tree for root measurements. Once a set of trees was selected for initial root measurements, we explored several procedural methods of pit excavation, trench wall marking, and root counting. We also explored different methods for characterizing the soil medium. Initial trenches did not include all measurements. Some added measurements and changes in data sheets (see Appendix 1: sample data sheet) were determined to be valuable or necessary, and changes were made as we encountered additional complexities and attributes of trees, levee sections, soils, and logistics of measurement.

Protocol

The adopted protocol for current root and tree measurements along the outfall canals in New Orleans are as follows (see sample data sheet, Appendix 1):

- Maps, photographs, and other documentation supplied by the Corp were used to aid in tree selections and field visits added confirmation to some of these selections. However, on-site field selection proved to be more efficient and was used for selecting most trees. Selected measurement trees and stumps were clearly marked with various combinations of temporary flags and brightly colored paint for the field measurement crew and other crews such as contractors, the Corp, etc.
- The general tree measurements to be taken were modified as needed. Some measurements could not be made on stumps of trees cut prior to sampling.. Therefore, not all data sheets include all measurements. General measurements include tree location (latitude and longitude), diameter at breast height (4.5 ft) (or specified height in the case of stumps and trees with abnormalities at 4.5 ft), tree height, and species (Figure 2). Tree-crown radius parallel to the measurement trench and crown radii in that direction and approximately normal to that direction were measured. Height and crown measurements are not available for stumps. Other measurements include distance from tree to toe of levee slope (Corp line

when marked) and distance from tree to the face of each successive trench wall if present.



TT: Distance from the tree to the toe of the levee

TD1,2,3: Distances from the tree to the corners and center of each trench

CR: Crown radius, measured perpendicular to the trench on the half of the tree closest to the trench

CD1,2: Crown diameters, measured both perpendicular and parallel to the trench

H: Total tree height

DBH: Diameter at breast height (4.5 feet from the ground)

Figure 2. Idealized diagram depicting typical measurements taken for trees studied along levees and floodwalls in the New Orleans area. Black boxes represent trenches and grey circles represent sample tree crowns. Not all measurements depicted could be taken on all trees, as some were felled and removed prior to measurement. Stump diameters were taken for trees felled prior to tree measurements.

- Generally, the first trench was at least 9 ft from the tree and successive trenches were placed at approximately 6 ft intervals away from the front wall of the previous trench (Figure 3, see Appendix 1 for additional examples). Additional trenches were added when roots in the current trench exceeded 0.5 inches in diameter. Reasons for discontinuing successive trenches were safety, working conditions, and insufficient distance from the trench to the levee wall. Some early trenching was discontinued because of conflicts with contract work for root and tree removal.

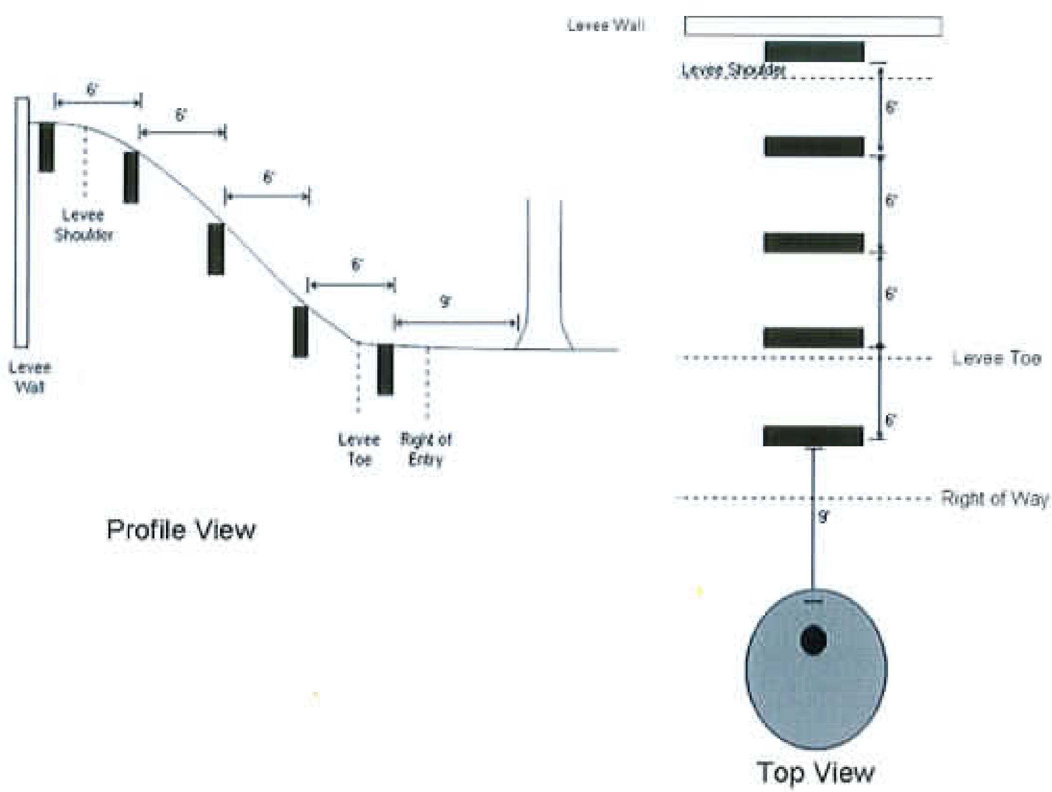


Figure 3. Idealized trenching diagram for root wall profile trenches used in this study. The black boxes represent an idealized trench placement along the levees/floodwalls in the New Orleans area. The first root profile trench cut for each tree (grey circle) generally was placed at least 9 ft from the base of a tree in the direction of the levee wall and parallel to it. Successive root profile trenches were spaced approximately 6 ft closer to the levee wall than each preceding trench. Successive trenches were excavated until there were no roots greater than 0.5 inches in diameter or conditions did not permit additional trenches (see text). Distance from tree to the first trench were varied to obtain a range of distances, species, and tree diameters.

- Trench and root related measurements (included descriptions, or samples associated with each measurement trench): Trench measurement zones extended from the soil surface to a depth of 3 ft and horizontally for 10-ft (at each trench location. The trench was roughly centered so that 5 ft of measurement wall occurred either direction from the approximate projected center of the measurement tree stem). The measured portion of each trench was divided into 1-ft vertical increments and 2-ft horizontal increments (some early work used 1-ft horizontal increments, but data were later combined into 2-ft increments) for a total of 15 root-measurement cells (Figure 4). Cell boundaries are delineated by temporarily placing a colored strand of rope or flagging at each 1-ft depth interval and cells across the measurement wall were delineated by vertical placement of colored flagging in strips at each 2-ft mark horizontally along the trench face.

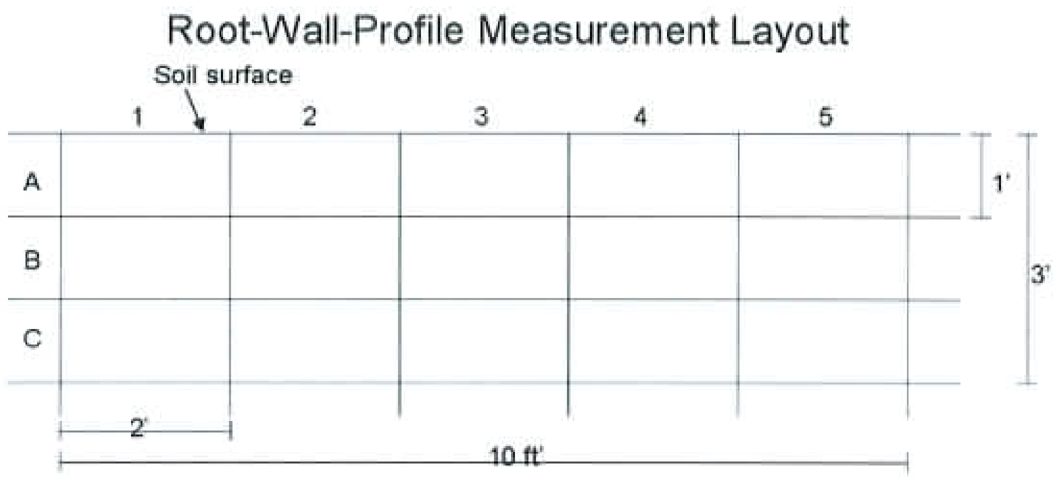


Figure 4. Idealized root-wall profile layout containing fifteen measurement cells. All roots greater than 0.5 inches in diameter were tallied within each cell.

- Measurements within the profile included the following:
    - soil texture by feel in each 1-ft layer with descriptions of uniformity and inclusions or other buried objects
    - soil strength measured with a pin penetrometer for each cell
    - roots were counted in each of three diameter classes (0.5 to 0.99; 1.0 to 1.49; and 1.5 to 2.0 inches) within each designated measurement cell
    - roots with larger diameters are measured with calipers and diameters were recorded
    - photographs were taken at each trench and often included both tree and trench views (See below)
    - All protocols were subject to modification as needed. Modifications generally included additional information and added measurements as different needs and conditions arose.

Photographic Documentation

For most trees after the initial data collection trials (protocol development), soil trench photographs were taken to record the general nature of the root systems. Some photographs are taken of trees as well (in a number of cases the trees were cut by Corp tree removal contractors before tree and root measurements had begun). Many measurement trees were documented with four pictures, one of the tree or stump, and three of the sample wall of the trenches. Photographs were labeled to correspond to trench identification code data (included on accompanying CD). Below are sample photographs depicting trees and trenches along the outfall canals in New Orleans.

Typical water oak, *Quercus nigra*, along the west side of the London Avenue Outfall Canal.

Early trench work for root measurements depicting initial protocol development.

Large root at ~ 7.5 ft depth in trench exploration work with Three Fold Consultants.

Root measurement cell delineation used to spatially segregate measurements of roots, soil strength, soil texture, and soil sample locations.

Compaction Quality Assurance

In order to verify standard compaction, JESCO proposed running In-Place Density Tests at various trench locations. JESCO tested the recompacted fill material in accordance with ASTM D 2922 (Nuclear Method). As described in the original workplan, One (1) trench was tested for every twenty (20) trenches excavated with the exception of the Lakefront and Mississippi River Abandoned Levee Sections. Regarding the Lakefront Levee, the New Orleans District requested a compaction test be performed on each observation trench developed directly in the Lakefront Levee. Additionally, the New Orleans District stated trenches did not require tests that were located completely outside the levee structure. Compaction tests were not performed at the abandon levee sections located near the Mississippi River Levee Sections in Bayou Goula and Cannonburg, LA.

Selected soil samples were collected from each investigation location and submitted to Beta Testing & Inspection, LLC (geotechnical laboratory) for analysis of Moisture Content (ASTM D2216), and Standard Proctor (ASTM D698A). The Standard Proctor and Nuclear Density results are shown as Appendix 7. The tested trenches were required to meet or exceed 90% compaction. All trenches tested met or exceeded the required 90% compaction.

The following information shows the number of trenches sampled during the study:

London Avenue Canal – 4 trenches tested, Passed

Orleans Canal – 2 trenches tested, Passed

Lakefront Levee – 26 trenches tested, Passed

17th Street Canal – 7 trenches tested, Passed

Mississippi River Levee Sect. 5155, 5070, & 4990 – Abandoned levees, No testing required

Mississippi River Levee Sect. 5595 – Abandoned levees, No testing required

Total # of Tests – Total of 39 trenches sampled (Total of 217 trenches in study)

Phase 3

Data Collection and Analysis

I. Data Collection

Tree Selection

Seventy-nine trees were selected for root-profile wall mapping (Table 1). Root extent of 54 trees along levees on the east and west side of the 3 outfall canals in northern New Orleans and 9 trees along the protection levee on the Pontchartrain lake front were sampled. Root extent of 16 trees were also sampled on and adjacent to the west protection levee along the Mississippi River south of Plaquemine Louisiana. All sampling occurred between April and June of 2007.

Table 1. Number of trees and species sampled on the New Orleans levees along the outfall canals into Lake Pontchartrain, the Lakefront of Lake Pontchartrain, and along the Mississippi River levee south of Plaquemine, Louisiana.

Species	Levee					Total
	17th Street	Lakefront	London Ave	Orleans Ave	MS river	
Baldcypress			4	4		8
Drake elm				1		1
Live oak	1	2	5	7		15
Pecan	4		3		5	12
Slash pine	1	7	1			9
Sugarberry	1		7	1		9
Sycamore			2	3	4	9
Tallow	3		2			5
Water oak	4		7			11
Total	14	9	31	16	9	79

Nine tree species were represented in the sample (Figure 5). Eight of these species are common to the outfall canals. In addition to sampling nine tree species, trees were selected to represent a range of diameters. Stem diameter was commonly measured at breast height (4.5 ft on the uphill side of the tree); for stumps (previously cut trees), however, diameter was measured near the top of the stump, and the height of the measurement recorded. The most common diameter for all sample trees was 16 inches. Of the smallest trees, a pecan and a slash pine, both were 13 inches in diameter. The largest diameter tree was a water oak, 64 inches in diameter.

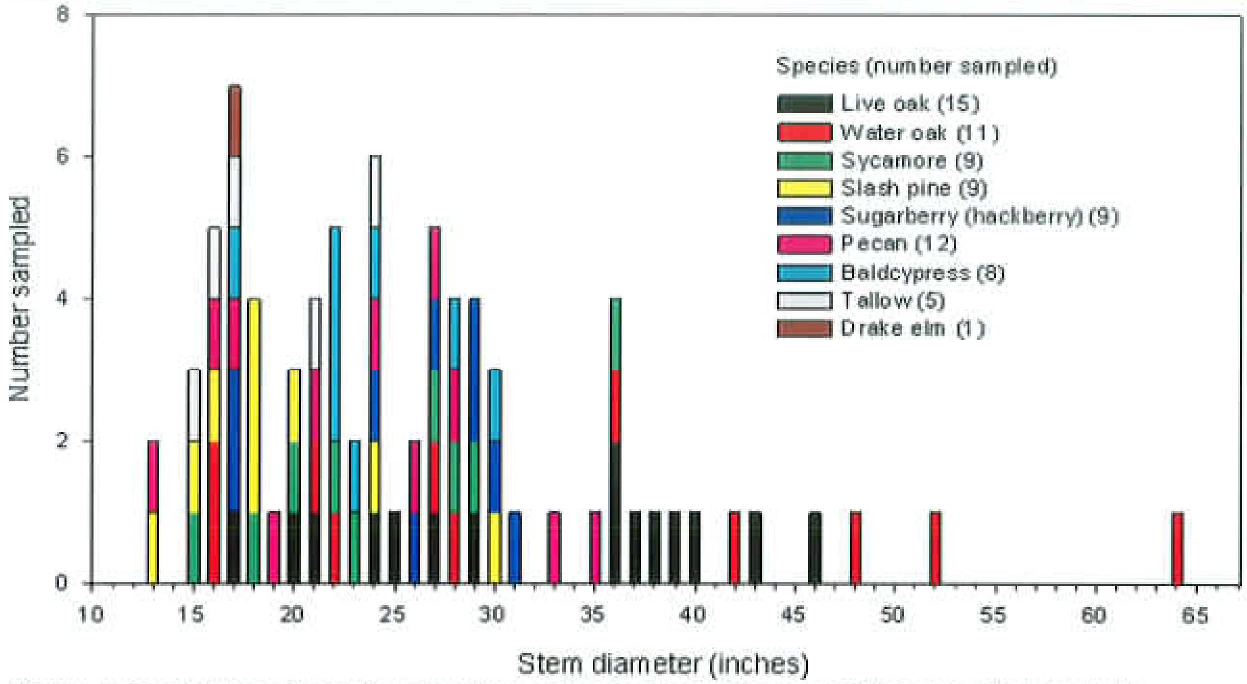


Figure 5. Distribution of tree diameters by species for New Orleans outfall canals, Pontchartrain Lakefront, and Mississippi River levee south of Plaquemine, Louisiana.

Trees selected for sampling root extent were located within a corridor extending from the toe of the levee to a distance where roots might extend. The outer boundary of the corridor was based on past measurement experience with a particular species and size combination. Ideally, trees were isolated enough to expect only the roots from the sample tree to be sampled on the root-profile wall, though roots of other species probably also protruded from the sample face on some occasions. Trees were selected along both sides of the London Ave canal and along a small section of the Pontchartrain lake front levee north of City Park (Figure 6a). The west side of the Orleans Ave canal had no trees (Figure 6b) so only trees on the east side were sampled. The baldcypress trees that were selected along the Orleans Ave canal were aggregated on the north end of the canal. Tree availability was also limited along the 17th Street canal (Figure 6c). Only pecan and sycamore were sampled along a small section of the Mississippi River protection levee (Figure 6d).

Within a particular species, the sample trees well represent the range of sizes encountered near the outfall levees (Table 2). In addition to stem diameter, total height of intact trees was measured with a sonic hypsometer (a few were measured with a laser hypsometer). Twenty-one trees were represented as remaining stumps at the time sampled. They had been cut prior to the initiation of this study. As mentioned in Phase II, radius of the live crown in the direction of the levee was measured with a 100-ft tape. Crown diameter was also measured in the direction of the levee and at right angles. These two diameters were averaged for the tree. Mean height of the sample trees ranged from 33 ft to 80 ft - the smallest tree was a 28-ft tallow tree and the tallest was a 110-ft sycamore tree.

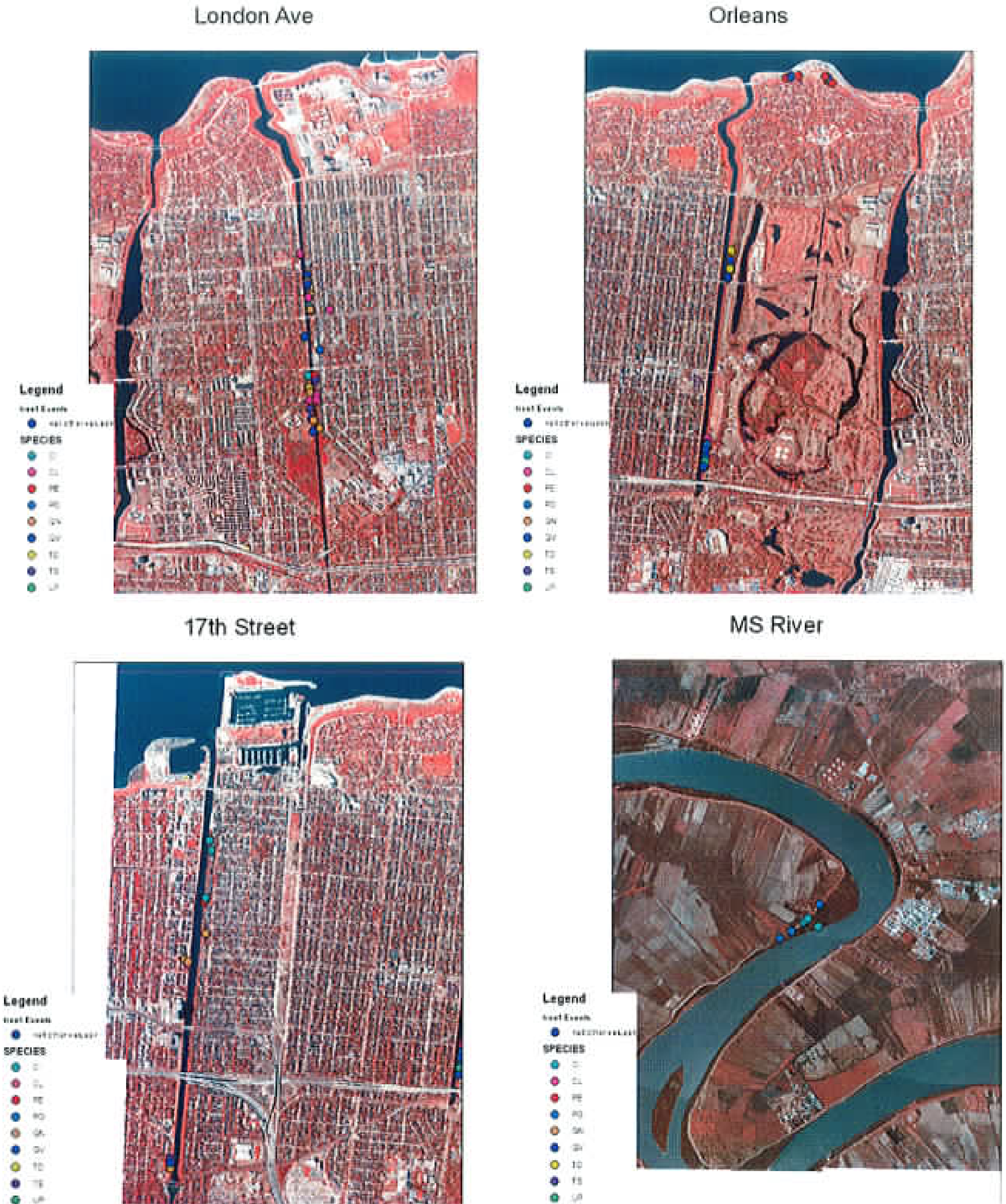


Figure 6a-d. Location of trees sampled along the London Ave Canal (a), the Pontchartrain Lakefront and Orleans Ave Canal (b), the 17th Street Canal (c), and the Mississippi River levee south of Plaquemine, Louisiana (d)

Legend Note (Species Code/Common Name): CI-Pecan, CL-Sugarberry, PE-Slash Pine, PO-Sycamore, PT-Loblolly Pine, QN-Water Oak, QV-Live Oak, TD-Bald Cypress, TS-Tallow, UP-Drake Elm

Table 2. Simple statistics grouped by species for four tree dimensions measured on trees selected for sampling root extension from the base of the tree on the New Orleans levees along the outfall canals into Lake Pontchartrain, the Lakefront of Lake Pontchartrain, and along the Mississippi River levee south of Plaquemine, Louisiana.

Species	Stem diameter				Height				Crown radius				Crown diameter			
	n	Mean	Min	Max	n	Mean	Min	Max	n	Mean	Min	Max	n	Mean	Min	Max
		--------inches-----------				-------------feet------------				-------------feet------------				-------------feet------------		
Baldcypress	5	25.2	21.8	30.0	5	56.1	36.0	65.3	4	14.1	10.0	18.0	4	31.7	24.0	35.8
Drake elm	1	17.1			1	32.9			1	21.7			1	44.4		
Live Oak	15	31.8	17.2	45.7	8	48.8	39.1	64.2	6	29.8	21.7	40.0	6	58.4	37.0	84.0
Pecan	11	23.5	13.0	35.4	10	70.3	49.6	88.0	9	29.6	10.7	43.5	9	47.1	27.7	69.0
Slash pine	9	19.2	12.5	30.2	7	50.0	41.3	57.1	7	16.8	7.0	24.3	7	30.3	22.8	39.1
Sugarberry	9	25.5	16.6	30.9	5	44.8	34.0	51.8	2	26.4	22.4	30.3	2	42.8	40.3	45.3
Sycamore	9	24.1	15.1	36.0	7	80.1	61.7	110.0	7	25.8	14.0	42.0	7	47.6	36.0	65.3
Tallow	5	18.7	15.1	23.5	5	44.7	28.5	57.1	3	22.1	15.0	27.3	3	34.0	32.4	35.9
Water Oak	11	33.8	15.9	64.0	6	60.6	45.0	86.0	3	23.9	20.0	27.8	3	50.7	45.2	55.1

The top of many trees appeared to be damaged from the hurricane or past storms; no attempt was made to correct these measurements. The mean crown radius was generally between 20 and 30 ft. The smallest crown radii were measured for baldcypress and for slash pine; the largest radii were observed for live oak and pecan. Crown diameter followed similar patterns to the crown radii. Some crowns had also suffered storm damage.

Table 3. Number and placement of 3 ft x 10 ft, root-profile trenches according to trees selected for sampling root extent from base of various species.

Species	Number of trenches	Mean number per tree	Distance from tree	
			Min	Max
			--------feet----------	
Baldcypress	14	1.8	8.6	24.5
Drake elm	3	3	9.7	20.6
Live oak	41	2.7	7.9	43
Pecan	43	3.6	8.2	61.8
Slash pine	29	3.2	8.1	37.5
Sugarberry	16	1.8	7.8	29.6
Sycamore	31	3.4	8.2	46
Tallow	14	2.8	6.7	28.3
Water oak	26	2.4	7.8	38

Root-Profile Walls

Radial root extent was estimated by counting roots protruding from one face of shallow trenches dug with a small excavator (see Phase II for details). Trenches were large enough to accommodate measurement root-profile walls that were 10-ft long and 3-ft deep. The right-of-entry corridor was often narrower than the corridor of roots with diameters of 0.5 inches or larger originating from candidate trees. For trees within the right-of-entry corridor, the first root-profile wall was generally dug approximately 9 ft from the base of tree. For trees outside the right-of-entry corridor, the first root-profile wall was created at the toe of the levee. Subsequent trench walls were excavated at approximately 6-ft intervals from the previous wall toward the ridge (shoulder) of the levee. Sampling was generally considered complete when less than 2 roots in the smallest root diameter category were present. Often, the final root-profile wall had no measurable roots. In a few instances, sampling was impeded by physical obstructions such as the flood wall for the levee. The shortest distance between the tree and the first root-profile wall was a function of tree location and the right-of-entry corridor; however, the maximum distance and to a limited extent, the number of trenches was a function of species (Table 3). The smallest maximum was observed for a Drake elm (a single tree) measured at the Orleans Ave canal, and the largest maximum was observed for pecans along the west protection levee of the Mississippi River. A total of 217 trenches were dug. Two of the trenches were 20-ft long to accommodate trees that were close together, but not too close; one of these long trenches was eliminated from the analyses because 3 trees were spaced along the trench at unequal distances. The other double trench had 2 trees about on the center of each 10-ft section; this trench was split in two and each section was analyzed for the tree within that section.

Roots

A grid 1-ft deep and 2-ft across was established on each root-profile wall. The number of roots in three diameter classes in each cell was recorded: 0.50 - 0.99 inches, 1.00 to 1.49 inches, and 1.50 to 1.99 inches. For roots larger than 2 inches in diameter, the actual diameter was recorded. Dead roots that were not rotten were also counted. Dead roots were combined with live roots since the objective in chronicling root extent was the possibility of large pores created by roots. Very few dead roots were counted.

The number of roots counted in the 0.50 to 0.99-inch diameter class was nearly one order of magnitude greater than the number of roots counted in next two diameter classes; they exceeded the number of roots greater than 2.0 inches by two orders of magnitude (Table 4). While the number of roots counted should be a function of species, the number counted for each tree is a function of the relative frequency of each species represented in the sample. Normalizing according the number trees selected by species: slash pine had the highest number of roots counted (44.9/tree on the root-profile wall surface) and sugarberry had the fewest number of roots counted per tree (13.7/tree on the root-profile wall surface).

Soil Strength and Textural Class

Root growth can be physically restricted by the soil's resistance to penetration or soil strength. This resistance can be estimated with a pin penetrometer. A Lang penetrometer was used to obtain an index of penetration resistance in each cell within the root-profile wall grid (15 readings per wall). This penetrometer gives an arbitrary reading between 0 and 20 depending on the force required to counter the friction of a pin moving into the soil with a calibrated spring. The scale value of 20 represents maximum resistance. According to the documentation, the scale is linearly related to load (see Appendix 2).

Normally, soil strength decreases with soil moisture content. A representative soil sample was collected at each 1-ft depth interval on the root-profile wall and placed in a plastic bag for transport to the lab where gravimetric soil moisture content was determined. For the soils sampled in this study, soil strength was linearly and negatively correlated with gravimetric soil moisture content for sand clays, sandy clay loams, clays, and clay loams (Figure 7). Penetrometer readings for these soils were corrected for moisture content when included in an analysis.

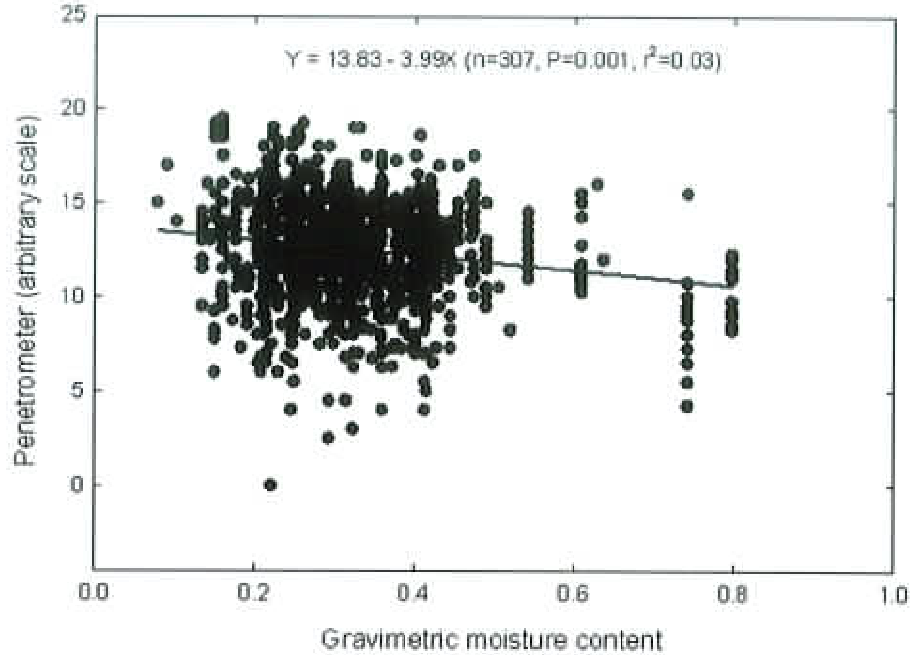


Figure 7. Scattergram of soil strength of clay soils and gravimetric moisture content samples collected in trenches dug on the New Orleans levees along the outfall canals into Lake Pontchartrain, the Lakefront of Lake Pontchartrain, and the along the Mississippi River levee south of Plaquemine, Louisiana. Line is ordinary least squares fit.

Normally, soil strength will increase with soil depth as a result of clay accumulation. Soils in the New Orleans area and along the Mississippi River levee are relatively young marine or river deposits mostly eliminating the vertical gradient in soil strength in more weathered soils. In addition, levees are constructed mostly from homogenized and compacted fill, minimizing variation in soil strength. The effect of the homogenizing factors is clearly evident in the penetrometer readings. The mean penetrometer reading for all depths and levees is 12.1 (Table 5). Within the top foot of the profile, the mean penetrometer reading was 11.2, and the within the bottom foot of the profile, the mean penetrometer reading was 12.2. Some heterogeneity is evident in the soils: penetrometer readings as readings ranged from a minimum of 1.5 to 3 to a maximum of 15.5 to 20. Mean soil strength did not vary predictably among horizons or among levees.

Table 4. Total number of roots counted on root-profile walls established in excavated trenches.

Species	Levee																				Totals			
	17th Street				Lake front				London Ave				Orleans Ave				MS River							
	Diameter class				Diameter class				Diameter class				Diameter class				Diameter class				Diameter class			
	0.75	1.25	1.75	>2.0	0.75	1.25	1.75	>2.0	0.75	1.25	1.75	>2.0	0.75	1.25	1.75	>2.0	0.75	1.25	1.75	>2.0	0.75	1.25	1.75	>2.0
Baldcypress									9	4	1	1	123	39	11	2					132	43	12	3
Drake elm													13	1	0	0					13	1	0	0
Live oak	9	0	0	0	7	1	0	0	109	14	9	4	162	44	4	5					287	59	13	9
Pecan	24	7	1	6					28	9	6	5					101	17	16	4	153	33	23	15
Slash pine	37	8	2	1	274	51	17	7	6	1	0	0									317	60	19	8
Sugarberry	17	4	1	4					65	20	7	1	4	0	0	0					86	24	8	5
Sycamore									45	20	11	18	7	2	1	0	71	32	11	12	123	54	23	30
Tallow	26	7	1	4					24	6	0	2									50	13	1	6
Water Oak	37	7	0	0					96	31	8	0									134	38	8	0
Total	151	33	5	15	281	52	17	7	382	105	42	31	309	86	16	7	172	49	27	13	1295	325	107	76

Table 5. Simple statistics for soil penetrometer readings by depth and by levee. Readings are arbitrary ordinal values between 0 and 20. Statistics based on single readings made in each cell of a 2 ft x 1 ft grid established on 10 ft x 3 ft root-profile walls in trenches excavated on the New Orleans levees along the outfall canals into Lake Pontchartrain, the Lakefront of Lake Pontchartrain, and along the Mississippi River levee south of Plaquemine, Louisiana

Levee	Depth (ft)											
	0-1				1-2				2-3			
	n	Mean	Min	Max	n	Mean	Min	Max	n	Mean	Min	Max
17th Street	205	10.3	3.0	17.5	206	12.3	5.5	19.5	202	13.0	4.3	19.3
Lakefront	130	13.6	6.5	18.5	130	12.3	6.5	19.5	130	11.6	2.0	19.0
London Ave	269	12.6	1.5	18.6	270	13.0	4.0	19.0	271	12.5	6.0	17.5
Orleans Ave	230	11.0	1.5	18.0	230	12.9	5.0	19.5	230	12.9	4.3	20.0
MS River	239	11.3	4.3	17.5	239	11.2	3.0	17.3	237	11.2	3.0	15.8

Mean penetrometer readings varied with textural class, with highest readings for finely textured soils (clay) and lowest readings for silty soils and coarse texture sands (Figure 8b). The textural class of the soil was determined at successive 1-ft intervals on the root-profile wall using a decision key (Appendix 3). Trenches were predominantly excavated in two textural classes: clay and silty clay (Figure 8a). The next two frequently encountered textural classes were clayey silt and silt. The frequency of these texture classes is consistent with soil origin in New Orleans and along the Mississippi River. It is also consistent with the geotechnical requirements of the levees. Sand was encountered on a few levees (Pontchartrain lakefront and the southern end of the London Ave canal). A layer of weathered brick was found in trenches excavated on the north end of the London Ave canal. Other items found in trenches were buried baldcypress stumps, large pieces of concrete, and old tile drains (see photographs).

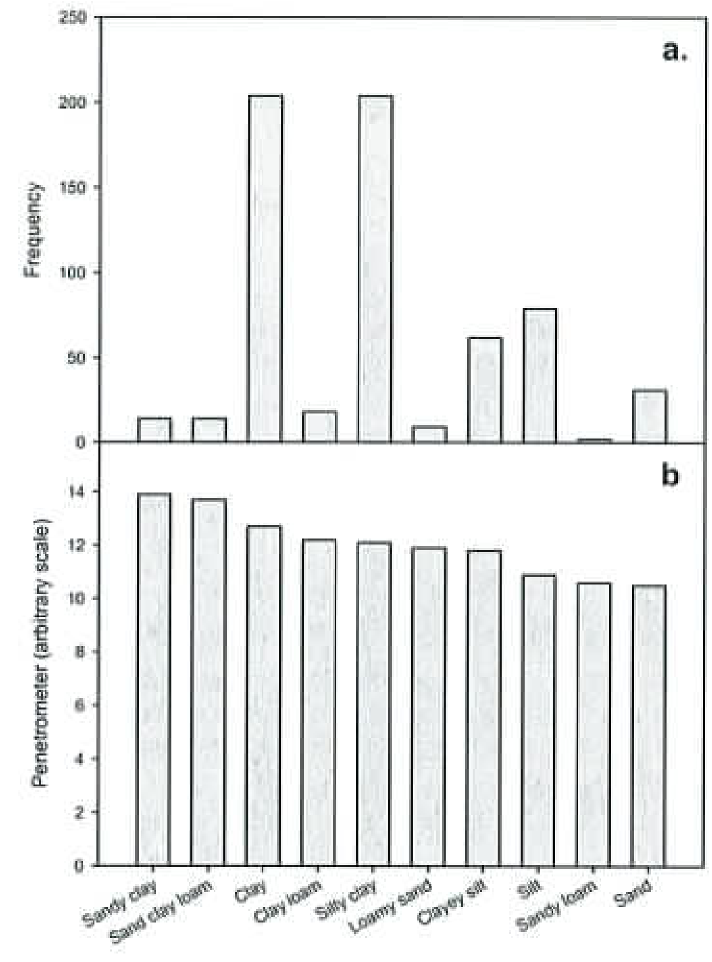


Figure 8. Frequency of soil textures encountered for each 1-ft layer of root-profile wall in trenches dug on the New Orleans levees along the outfall canals into Lake Pontchartrain, the Lakefront of Lake Pontchartrain, and along the Mississippi River levee south of Plaquemine, Louisiana and average penetrometer readings for each texture classification.

Root-profile wall with clayey silt texture

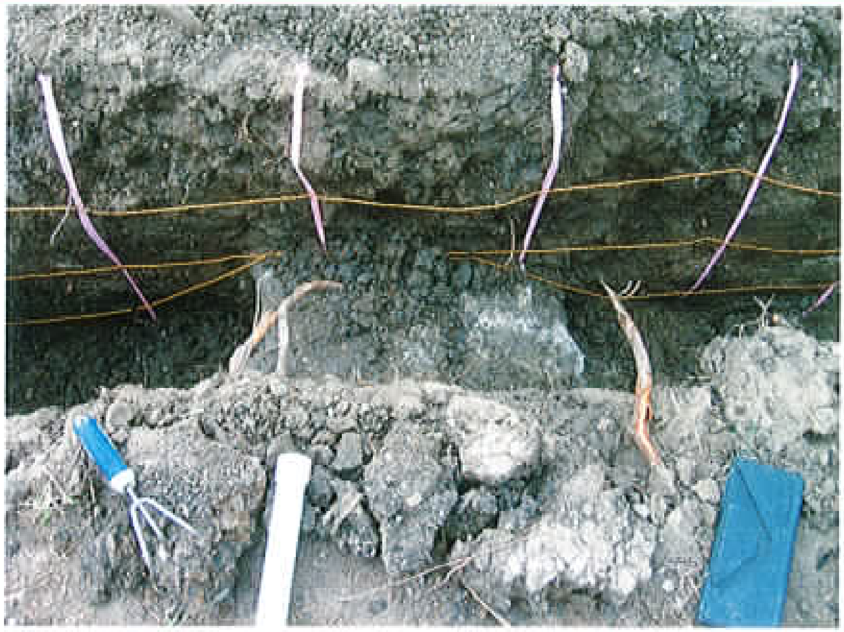
Root-profile wall with silt texture

Root-profile wall with sandy soil texture

Root-profile wall with sandy soil texture

Weathered brick found in sections of London Avenue root-profile walls

Buried cypress stumps within root-profile wall section



Large pieces of buried concrete within root-profile trench

Large pieces of buried concrete within root-profile trench

II. Results

Root Frequency and Radial Extent

For all species, the number of roots greater than 0.5 inches in diameter decreased with distance from the base of the tree (Figure 9). Roots greater than 1.0 inch also decreased with distance from the tree, but since substantially fewer roots in the larger size classes protruded from the root-profile walls, the pattern was far less pronounced. Because so few roots greater than 1.5 inches in diameter were counted on the 30 ft^2 root-profile wall surface, no apparent relationship existed between number and distance for this size class.

To determine factors influencing the number of roots above the three minimum-size categories, correlation coefficients were calculated between the logarithm of root counts and distance, and other tree and soil properties. The counts were transformed because the decline in root counts with distance from the tree resembled an exponential decay function. Distance was consistently correlated with the logarithm of counts for all three minimum size categories (Table 6). For roots greater than 1.5 inches, distance was the only variable that correlated with the log of counts. For roots greater than 1.0 inches, stem diameter was also significantly correlated with root counts. For roots greater than 0.5 inches, stem diameter, tree height, and a simple volume index based on diameter and height were also correlated with root counts. Soil strength was not correlated with root counts for any of the root size categories.

Table 6. Correlation coefficients of logarithm of number of roots above three minimum root-diameter classes counted on the root-profile walls with distance from the tree and various physical characteristics of the trees and soil. P value for the hypothesis r = 0.

Variable	> 0.5		>1.0		>1.5	
	r	P	r	P	r	P
Stem diameter (D)	0.063	0.212	0.16	0.026	0.0432	0.657
Tree height (H)	-0.072	0.22	0.05	0.557	-0.011	0.921
D squared x H	0.068	0.244	0.135	0.114	0.0266	0.817
Crown diameter	-0.173	0.008	-0.119	0.219	0.154	0.231
Crown radius	-0.173	0.008	-0.114	0.237	0.097	0.453
Distance from tree	-0.37	<0.001	-0.351	<0.001	-0.281	0.003
Soil strength index	-0.04	0.455	-0.063	0.391	0.089	0.369

To simultaneously account for the effect of variables, the logarithm of root counts was related to distance, species, depth, soil strength, and stem diameter using covariant analyses and the General Linear Models procedure in SAS (ver 9.1). No interactions were included in the model. For roots greater than 0.5 inches in diameter, all variables significantly affected the number of roots protruding from a root-profile wall (Table 7). For roots greater than 1.0 inch in diameter and greater than 1.5 inches in diameter, all variables with the exception of soil strength affected root counts. Coefficients for individual variables can be estimated with the General Linear Models procedure: they are not unique solutions, but indicate direction and relative strength of the effect. For each diameter category, the number of roots protruding from the root-profile walls varied with species, decreased with depth, and increased with stem diameter. Roots greater than 0.5 inches decreased with increasing soil strength. As

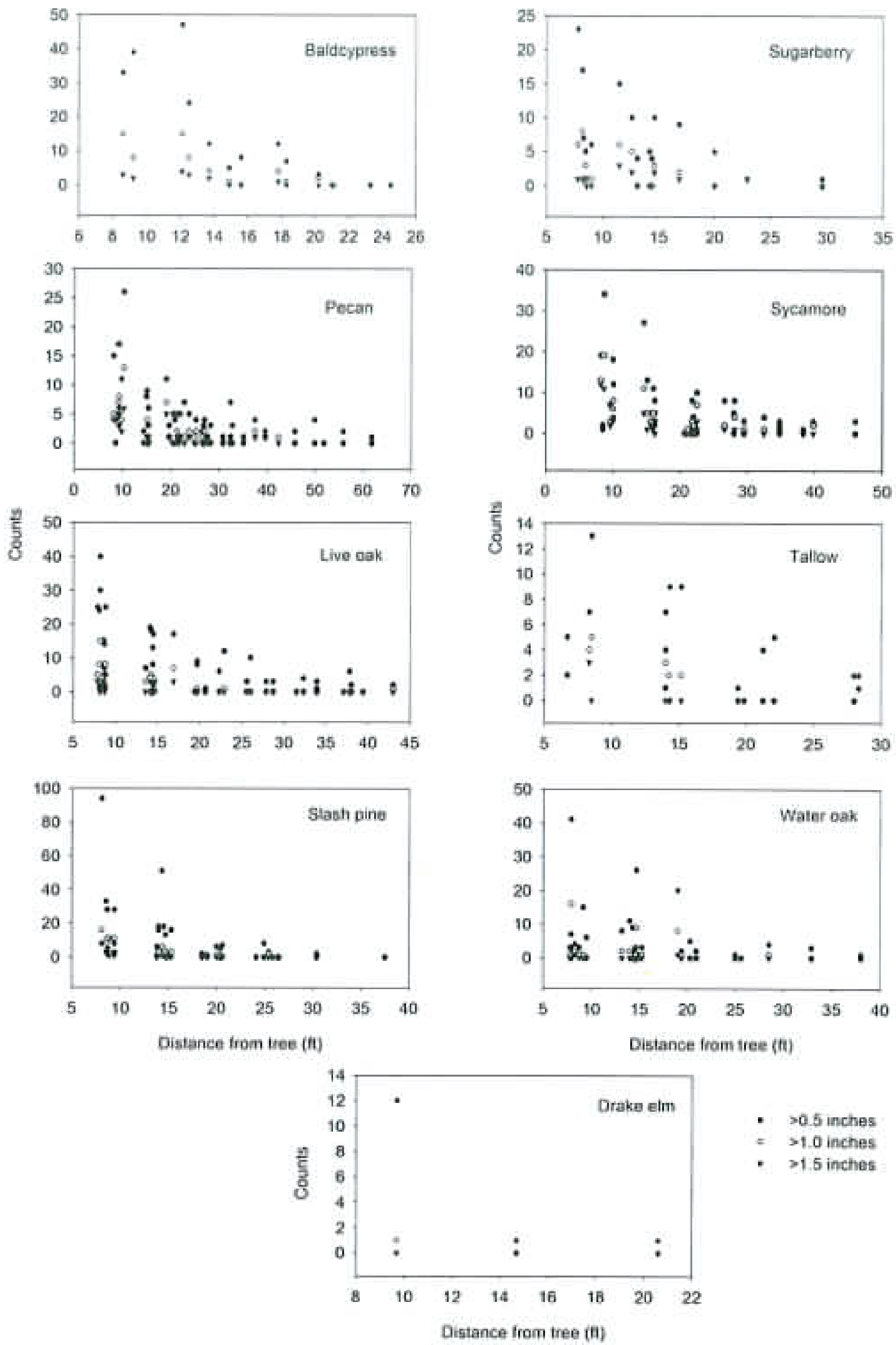


Figure 9. Number of roots counted on root-profile walls above three minimum root-diameter classes as function of distance from the base of the tree by tree species.

indicated by the value of R^2, nearly 70 % of the variation in the number roots per profile wall was left unexplained with this model.

Table 7. Results of covariant analysis for the logarithm of root counts above three different size thresholds for all levee locations.

Variable	df	Size class		
		>0.5 inch	>1.0 inch	>1.5 inch
		P	P	P
Species	8	<0.001	<0.001	0.155
Horizon	2	<0.001	0.034	0.102
Distance	1	<0.001	<0.001	<0.001
Stem diameter	1	<0.001	<0.001	0.032
Soil strength	1	0.084	0.102	0.218
Error	372			
R square		0.313	0.313	0.248

Apparent Maximum Radial Extent

The distance from the tree, where the number of roots protruding from a root-profile wall was one or less, was assumed to be the maximum radial extent of roots emanating from the subject tree to a depth of 3 ft. The actual tips of the roots were not located. Maximum extents were determined for each of the root diameter thresholds. Correlation coefficients between maximum root extent and tree characteristics were generally significant for roots in all three diameter categories (Table 8). Maximum root extent was significantly correlated with soil strength for any diameter threshold. Since soil strength was related to soil texture (Figure 7), the absence of a correlation between penetrometer reading and radial extent suggests there was no effect of the type of soils encountered in these levee trenches and how far roots extend from the tree. For roots greater than 0.5 inches and greater than 1.0 inches, the index of stem volume (D^2H) showed the highest correlation with maximum root extent: tree height and crown size were the next most correlated variables. For roots greater than 1.5 inches in diameter, crown diameter showed the highest correlation with root extent.

Table 8. Correlation of maximum root extent as measured by the distance from the tree of root-profile walls with less than one root above three minimum root diameter classes with physical dimensions of the tree and penetrometer readings.

Variable	>0.5		>1.0		>1.5	
	r	P	r	P	r	P
Stem diameter (D)	0.303	0.043	0.183	0.135	0.272	0.021
Height (H)	0.547	0.001	0.23	0.042	0.168	0.234
D squared x H	0.64	<0.001	0.351	0.014	0.261	0.062
Crown diameter	0.56	0.001	0.267	0.091	0.418	0.006
Crown radius	0.571	0.001	0.284	0.072	0.263	0.092
Soil strength index	0.007	0.964	-0.059	0.632	0.018	0.878

The maximum radial extent of the roots is related to tree species, but the specific rankings vary by the diameter thresholds of the diameter class (Table 9). The furthest average extent was seen in roots > 0.5 inches in diameter for pecan. Sycamore roots extended the furthest for roots greater than 1.0 and 1.5 inches. The maximum extents of sugarberry roots in the various size classes were approximately half the extent of the pecan and sycamore roots.

The maximum extent of water oak roots greater than 1.0 and 1.5 inches were nearly the same as sugarberry. While specific species rankings varied with each diameter threshold, species were consistently in the top or bottom halves of the rankings, with exception of baldcypress. For example, the maximum radial extent of live oak roots ranked second in the two smallest root thresholds and fourth out of nine in the largest threshold class. The maximum extent of Drake elm roots ranked last in every class.

Table 9. Species ranking according to radial extent of roots for three minimum size thresholds for all levee locations.

>0.5 inches		>1.0 inches		>1.5 inches	
Species	Max extent (ft)	Species	Max extent (ft)	Species	Max extent (ft)
Pecan	34.4	Sycamore	25.2	Sycamore	21.2
Live oak	25.6	Live oak	19.2	Baldcypress	17.4
Sycamore	25.6	Slash pine	19.2	Pecan	17.3
Slash pine	24.3	Pecan	18.4	Live oak	17.1
Baldcypress	22.5	Tallow	18.3	Slash pine	14.3
Water oak	22.1	Baldcypress	18.0	Tallow	13.2
Tallow	19.6	Sugarberry	13.8	Water oak	12.9
Sugarberry	15.8	Water oak	12.9	Sugarberry	11.5
Drake elm	14.7	Drake elm	9.7	Drake elm	9.7

The edge of the crown is commonly thought to demarcate radial root extension. If true, the slope between the maximum radius of roots and crown radius would be one. Our estimate of maximum root extent regressed against crown radius had slopes of 0.5 and smaller for three categories of root sizes. Plots of the resulting equations indicate that on average, roots greater than 0.5 inches in diameter do not extend past the edge of the crown, at least not in the direction of the levee (Figure 10). Roots greater than 1.0 inch and greater than 1.5 inches in diameter extend on average to half way between the stem and the edge of the crown. As is evident in scattergrams of the data, linear regression only explains 33% of the variation in the radial extent of roots greater than 0.5 inches in diameter; it explains less than 10 % of the variation in the larger root categories.

Distance and Cumulative Fractions of Root Extent

Given the high variation in root extent observed in this study, probabilities of how far roots extend may be more informative than deterministic approaches such as correlation and regression analyses. Probabilities are determined by fitting probability density functions to frequency data. While many probability functions exist, the 3-parameter Weibull function possessed properties consistent with the nature of the data and objectives of the analysis. The domain of the function in relative terms ranges from 1 to infinity, which corresponds to the uncertainty of the absolute maximum a root may extent from the tree. The function can be fit to absolute values as well as relative values. The function can account for a variety of shapes, and it is easily transformed

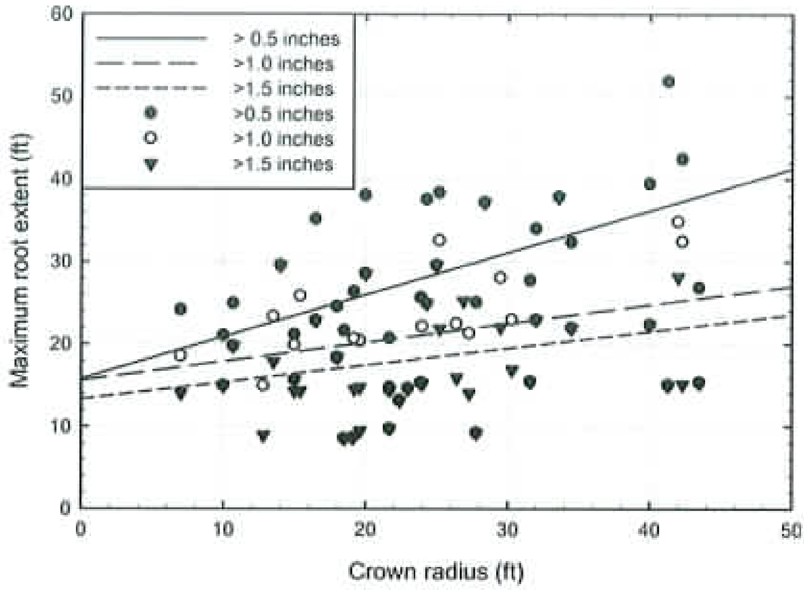


Figure 10. Scattergrams of maximum root extent estimated as the distance from the tree that a root-profile wall had less than 2 roots showing against the crown radius in the direction of the levee. Lines fitted with linear regression.

into a cumulative probability function. With the cumulative probability function, the distance from the tree encompassing specific cumulative fractions of root within a volume of soil 3-ft deep and 10-ft across can be calculated (Appendix 4). The cumulative fraction of roots contained in that volume increases with distance at a decreasing rate, never reaching one. In other words, while the probability of finding roots beyond a given distance diminishes with distance, it is never zero according to this analysis. From a practical standpoint, this allows the probability of roots extending beyond a certain distance to be compared to the risk of roots extending beyond that point.

With the exception of the roots greater than 1.5 inches in diameter, the cumulative Weibull function fit the accumulation with distance from the tree of roots counted on the root-profile walls (Figure 11 a-c). The poor fits reflect the small number of roots counted in the largest threshold class. No analysis was conducted Drake elm roots larger than 1.5 inches since only one root was counted in this size class. The end of the curves corresponds to the maximum distance a root-profile wall was dug for a particular species. These maximums are another expression of species differences in the radial extent of roots.

The distance corresponding to cumulative fractions of 0.50, 0.90, and 0.95 of roots counted on the root-profile walls were determined from the fitted cumulative density functions for each species. Half of the roots greater than 0.5 inches in diameter protruding on the root-profile walls were within 12 ft of the tree (levee side) for all but pecan and sycamore. Pecan required the longest distance to account for 50% of the roots greater than 0.5 inches counted on the root-profile wall: 15 ft. Fifty percent of the roots greater than 0.5 inches were within 11 ft of the tree for baldcypress, slash pine, sugarberry, and water oak (Table 10). Ninety-five percent of the roots greater than 0.5 inches in diameter were counted on the root-profile walls within 37.8 ft of pecan trees. Ninety-five percent of the roots greater than 0.5 inch in diameter were counted on root-profile walls at distances of less than 28 ft for live oak, tallow, and water oak, and at distance of less than 19 ft for baldcypress, slash pine, and sugarberry.

The paucity in the number of roots greater than 1.5 inches that were counted on the root-profile walls produced poor fits of the Weibull function to the data collected for water oak. Half of these roots can be expected within about 13 ft of the tree. The closest distance where half of the roots in this size class were counted was slash pine at 9 ft. Thirty feet was needed to account for 95% of the roots greater than 1.5 inches for pecan. For the other species, 95% of the roots in this size class can be expected just over 20 ft from the tree. Ninety-five percent of slash pine roots greater than 1.5 inches are expected within 12.1 ft. of the tree.

Table 10. Distances associated with three cumulative fractions of roots above three minimum root diameters by species. Distances determined from Weibull probability density functions fitted to roots counted on 3 ft x 10 ft root-profile walls and distance from the base of the tree.

Species	>0.5			>1.0			>1.5		
	0.5	0.9	0.95	0.5	0.9	0.95	0.5	0.9	0.95
	--------------ft--------------			--------------ft--------------			--------------ft--------------		
Baldcypress	10.7	15.8	18.0	10.5	15.5	17.6	10.7	15.6	17.7
Drake elm	10.5	12.7	13.6						
Live Oak	12.0	21.5	25.6	10.1	15.2	17.4	9.5	13.1	14.7
Pecan	15.0	30.9	37.8	13.3	25.2	30.3	13.2	24.9	30.0
Slash pine	10.6	16.4	18.9	10.0	14.6	16.5	9.0	11.1	12.1
Sugarberry	10.4	16.3	18.9	9.3	14.2	16.3	11.4	18.8	22.0
Sycamore	13.8	27.1	32.7	12.8	23.5	28.1	11.2	18.2	21.2
Tallow	11.4	22.3	27.1	10.0	17.8	21.1	10.0	17.8	21.2
Water Oak	10.9	17.9	21.0	9.6	13.7	15.5	7.6	8.4	8.8

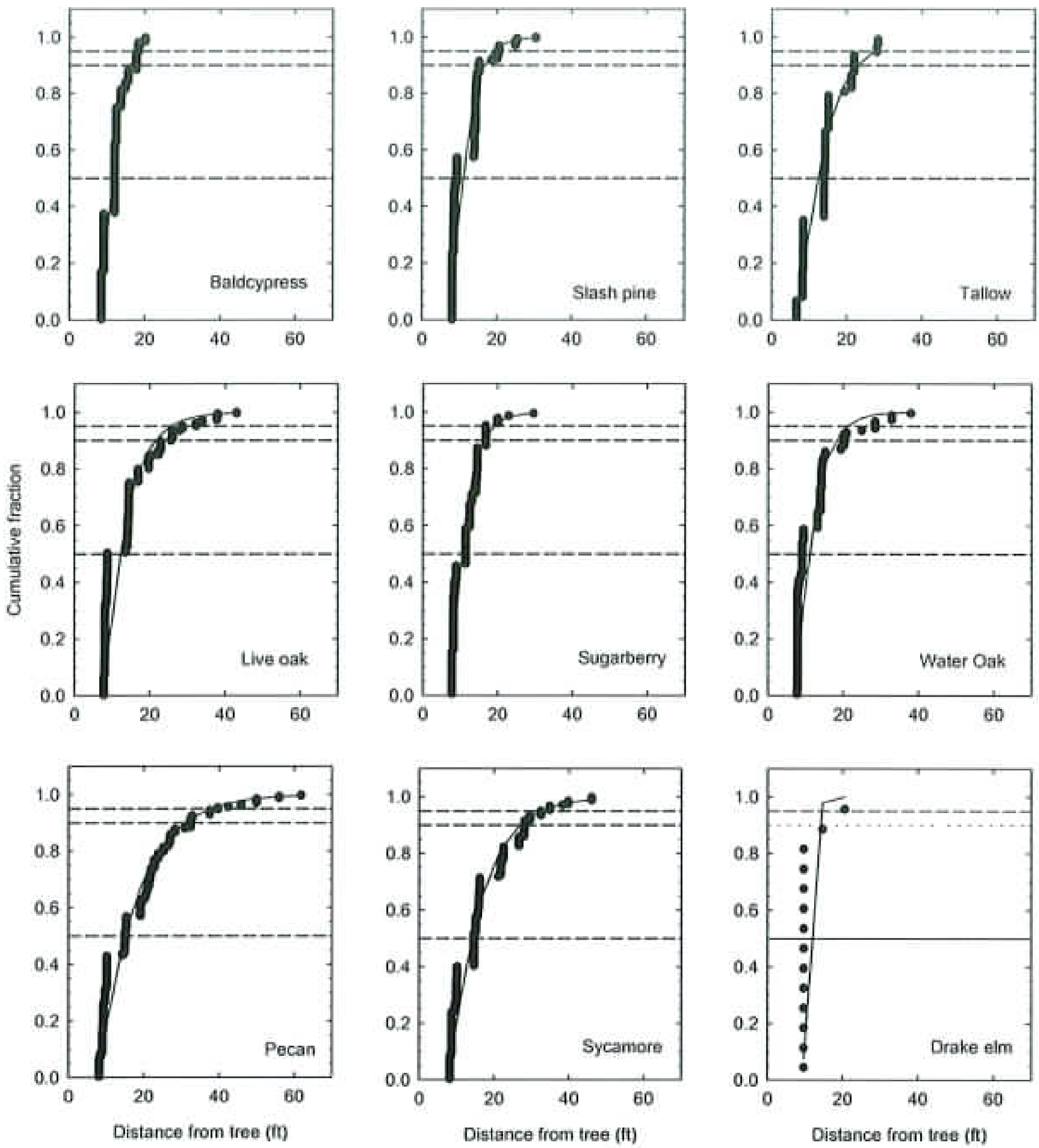


Figure 11a. Cumulative fraction of roots greater than 0.5 inches as a function of distance from the base of the trees for the various species included in sample. Lines from Wiebull function fitted to root counts using maximum likelihood. Horizontal lines indicate 0.5, 0.90, and 0.95 cumulative fractions.

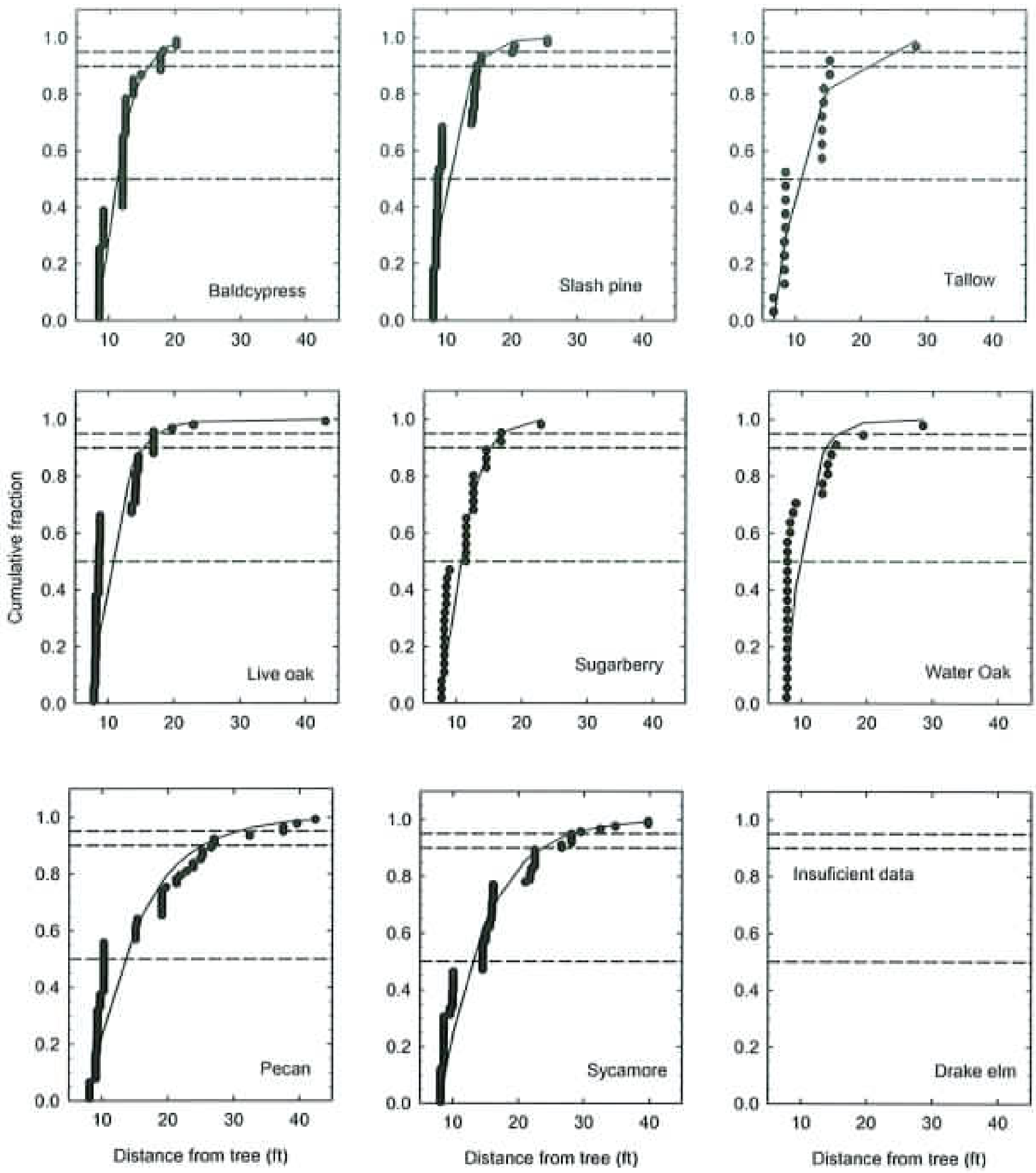


Figure 11b (continued). Cumulative fraction of roots greater than 1. inches as a function of distance from the base of the trees for the various species included in sample. Lines from Weibull function fitted to root counts using maximum likelihood. Horizontal lines indicate 0.5, 0.90, and 0.95 cumulative fractions.

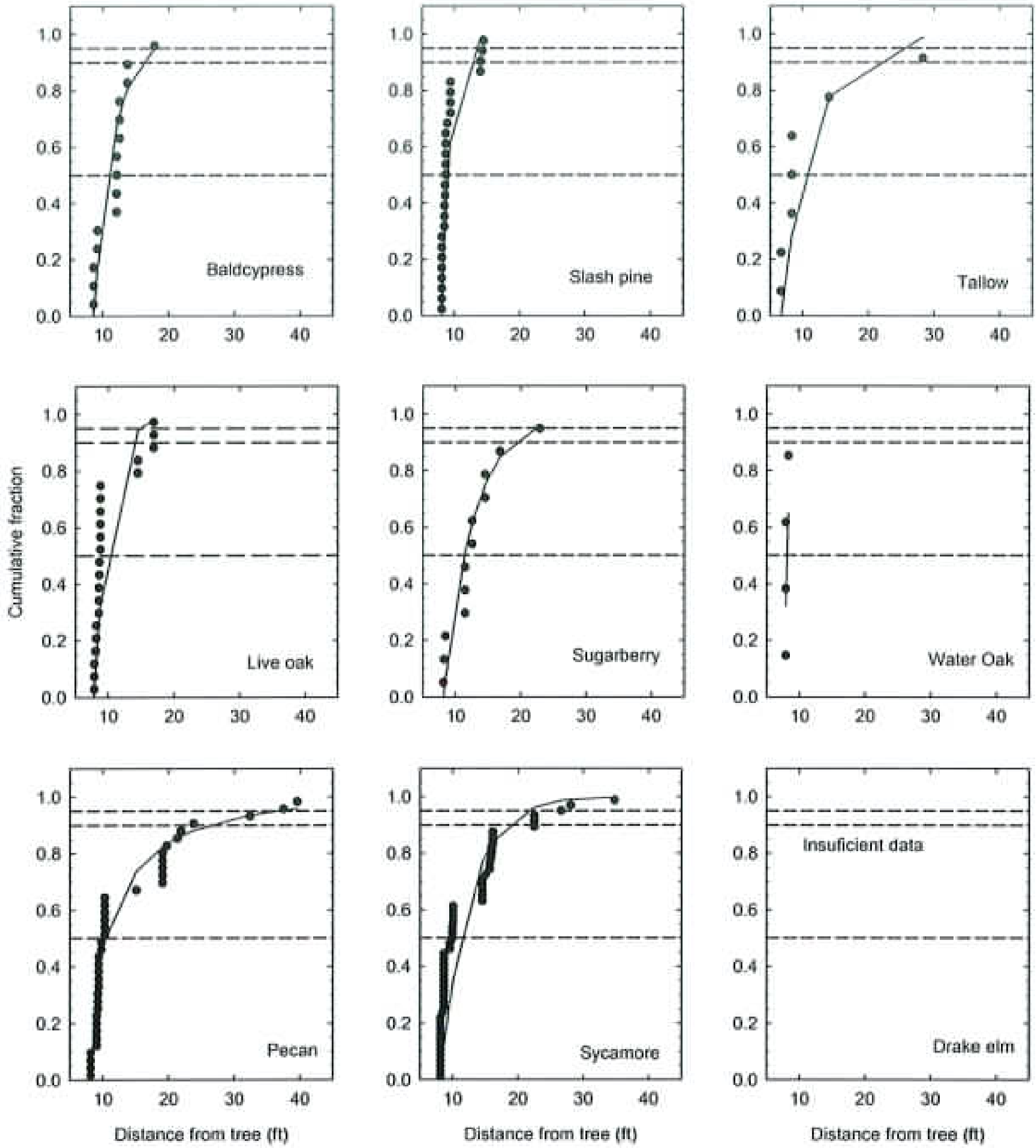


Figure 11c (continued). Cumulative fraction of roots greater than 1.5 inches as a function of distance from the base of the trees for the various species included in sample. Lines from Wiebull function fitted to root counts using maximum likelihood. Horizontal lines indicate 0.5, 0.90, and 0.95 cumulative fractions.

Effect of Soil Type on Cumulative Fractions

The physical properties of the soils were significantly different along and on the levees of the outfall canals in New Orleans and the along the protection levees of the Mississippi River. Adequate numbers of pecan and sycamore were sampled in New Orleans and along the Mississippi River levee to investigate the effect of different soil types on the cumulative percentages of roots with distance from the tree. Weibull functions were fit to the root count data for each combination of species, location, and depth. The distances corresponding to 50, 90, and 95% of the roots protruding from the root-profile walls were analyzed with a randomized, complete-block design with depth serving as a blocking variable. For roots greater than 0.5 inches in diameter, species differed in the distance corresponding to all three cumulative percentages (Table 11).

Differences between levees were detected in the distance containing 95% of the roots but at distances for smaller accumulations. At this distance, levee location and species interacted in that 95% of the roots for pecan are expected at 35 ft in New Orleans and at 45 ft along the Mississippi River levee, whereas 95% of sycamore roots are expected at 22.5 ft in New Orleans area and only 21 ft along the Mississippi River levee. No species or levee location effects were detected for any of the cumulative percentages for roots greater than 1.0 inch. Levee location influenced the distances associated with cumulative percentages of 50%, 90%, and 95% of roots greater than 1.5 inches in diameter. For this size class, longer distances are required along the Mississippi River levee to encompass the same percentage of roots along the New Orleans outfall canal levees by as much as 13 ft.

Table 11. Statistical comparison of levee location (New Orleans outfall canal levees (NO) vs. Mississippi River levee MS)) and species (pecan vs. sycamore) on distance from the tree (ft) corresponding with three cumulative fractions of roots as determined from Weibull probability density functions fitted to the data by species, location, and horizon.

Species	>0.5 inches			>1.0 inches			>1.5 inches		
Levee	0.5	0.9	0.95	0.5	0.9	0.95	0.5	0.9	0.95
				ft					
Pecan									
NO	14.4	28.9	34.9	13.0	24.9	30.1	10.8	20.4	24.5
MS	17.2	36.9	45.5	14.1	26.0	31.2	14.6	26.7	31.9
Sycamore									
NO	11.1	18.0	22.5	10.5	16.0	18.4	9.7	13.4	15.0
MS	6.0	17.5	21.0	14.4	27.4	33.0	13.8	24.1	28.6
P values for effect									
Species (S)	0.073	0.001	<0.001	0.43	0.355	0.348	0.573	0.244	0.218
Levee (L)	0.736	0.148	0.038	0.123	0.189	0.199	0.075	0.09	0.0947
S x L	0.276	0.109	0.093	0.3	0.227	0.2212	0.955	0.564	0.52
df error	6	6	6	4	4	4	8	8	8
RMSE (ft)	5.7	4	4	1.8	5.6	7.2	2.3	5.4	6.8

The mean strength of the soil sampled along the levees in New Orleans was statistically greater than the mean soil strength sampled along Mississippi River levee south of Plaquemine (Table 12). Root growth may be related more closely to minimum values of soil strength than mean values, but the difference in the minimum penetrometer reading recorded near the Mississippi River levee was not statistically different from the minimum penetrometer reading recorded along the levees in New Orleans. The maximum penetrometer readings recorded at the Mississippi River levee site was also only one unit lower than that recorded along the New Orleans levees, but in this case the difference was consistent enough to be statistically significant. Apparently, root extension of the pecan and sycamore trees was not sensitive to these apparently small differences in either mean or maximum differences in soil strength since canal location had no statistically significant effect on the distance associated with the various cumulative fractions of root counts for any size class of roots.

Table 12. Statistical comparison of mean, minimum, and maximum soil strength measured on and along levees in New Orleans and along a section of the Mississippi River protection levee.

Levee	Mean	Min	Max
New Orleans outfall canal levees	12.5	10.2	14.2
Mississippi River levee	11.5	9.3	13.1
P values for effect			
Levee (L)	0.030	0.210	0.053
df error	4	4	4
RMSE (ft)	0.8	1.8	0.4

Root Depth

Exploration of root depth was conducted on abandoned sections of levee along the Mississippi River. For selected species, trenches were excavated to the limit of the mini-excavator used (about 7.5 to 8 ft deep). Ten trees representing 5 species were selected (Table 13). Since the trenches exceeded a depth of 4 ft, measurements were generally not taken of root diameters because of the possibility of the wall caving-in. Instead, we measured root depths with a rule and made ocular estimates of diameters of roots occurring at maximum depth within each trench. Occasionally accurate root diameter measurements were possible from narrow benches of shallower depths. The abandoned levees were covered with relatively young trees in most instances, but occasionally trees were quite large. Since trees were often in close proximately to each other, sample trenches were often placed between adjoining trees. Trenches were expanded lengthwise or in other directions as needed to explore or trace roots that seemed to be oriented in a more oblique or vertical manner. All estimated root depths were for roots that appeared to exceed 0.5 inches in diameter.

Table 13. Characteristics of trees selected on abandoned levee sections for exploration of roots between 3 ft and 8 ft below the surface

Species	n	Tree DBH (inches)	
		min	max
Baldcypress	1	15.5	15.5
Live oak*	1	11.7	20.4
Pecan	2	16.4	24
Sugarberry	5	7.6	20.7
Sycamore	3	13.8	26.0

*Forked

At least in the trench areas that we sampled, few roots of any size existed between 3 and 8 ft. We did not find any roots next to a baldcypress tree that were deeper than 4 ft. We measured three small sugarberry trees along a common trench and did not find roots deeper than 4 ft. A 14.0-inch diameter sugarberry had a small root at 6.5 ft below the surface at a horizontal distance of 7.5 ft from the tree. A 20.7-inch DBH sugarberry had 0.5 inch diameter root at 8.3 ft depth and 1.0 inch diameter roots at 5.3 and 7.0 ft depth. One pecan (16.4 inch DBH) with maximum root depths of 5 ft (0.5 inch diameter root 8 ft from tree), 7.0 ft (7 ft from tree), and 7 ft (19 ft from tree), was accessed by three trenches.

A 24-inch diameter pecan had 2-inch diameter root 4-ft deep and 1.6-inch diameter root at a 6 ft depth. These roots were measured from a trench 8 ft downslope from the tree. The tree also had one vertical root exceeding 1.75 inches at a depth of at eight feet deep. Roots measured in a trench 10 ft upslope from the tree included a 1-inch diameter root 6.1 ft deep along the back wall of the trench, a 1 inch diameter vertical root in the bottom of the pit at 7.5-ft deep, and roots approximately one-half inch or greater in diameter at 8.5 ft deep. Vertical roots that we saw penetrated to depths deeper than we could excavate with the available equipment.

Roots from the live oak with a forked main stem exceeded half an inch at 4 ft depth, but one root was traced 30 feet from the tree downslope until it was lost under a large sugarberry. A 26-inch diameter sycamore was growing on a steep slope just above a ponded area. In an adjacent trench 9 ft from the tree, three roots of 2-, 1-, and 0.75-inch diameters were found at depths of 3.8 ft, 5.0 ft, and 6.9 ft, respectively. In a trench 13 ft from the same tree, root diameters of 1, 0.5, and 1 inch were found at depths of 0.73 ft, 5.3 ft, and 6.1 ft, respectively. Large diameter roots do exist deeper than the 3 ft depths we measured in most of the root-profile walls.

Few roots of any size were found below 3 ft in a typical trench. The deepest the miniexcavator could reach was 8.5 ft.

No roots deeper than 4 ft were found next to this baldcypress tree.

Trenching pattern resulting from tracing one deep root between two trenches.

One root was traced between two parallel trenches to a depth of 8 ft. The mini excavator could not dig below that depth. Deep roots were few in trenches excavated on the abandoned Mississippi River levee sections that were explored

Trench excavated upslope of a pecan tree on an abandoned levee section.

III. Data Gaps and Future Research

The largest deficiency in this study is the paucity of roots in the larger diameter classes (within the 10 ft trench per tree), especially those greater than 1.5 inches in diameter (Table 4). We counted 8 roots > 1.5 inches in diameter for water oak in our sample, and excluding pecan and sycamore, 2 roots in this size class per species was a typical count. If the ratio of larger roots per root-profile wall is typical, another 200 root-profile walls would need to be dug to equalize the sampling frequency of roots > 1.5 inches with the sampling frequency of roots > 1.0 inches.

The number of species included in the study appeared representative of the dominant species along the New Orleans outfall canals. Live oak, pecan, and water oak were sampled most frequently. Sugarberry was numerous along the levees, but few were sufficiently isolated to adequately sample roots for an individual tree. Additional root-profile walls for the underrepresented species would strengthen species comparisons.

Equations for describing the number of roots protruding from a root-profile wall as a function of distance from the base of the tree accounts for at most 31% of the variation in root counts - 25% for the largest size class of roots. Consequently, estimates of maximum radial extent of roots of the various size thresholds are extremely variable. In the smallest size class, the maximum extent varied from 20 to over 50 ft for the largest trees (Figure 11a-c). The only means of increasing the reliability of that number is to increase the number of trees sampled. Our recommendation is to continue development of the probability of roots of a given minimum size class that will extend past a specified distance. While larger sample sizes would improve these estimates, probabilities overcome the possible liability that some minimum safe distance exists.

Sampling and time limitations confounded two questions: how far do major roots extend and how do roots behave within a levee section. These questions can be formulated as one question: does root extension change when encountering a levee? To answer that question root growth and extension need to be measured on undisturbed soil, for urban conditions. Access limitations and obvious land owner concerns prevented us addressing this question directly. We were able to address the question indirectly by comparing root extension of pecan and sycamore in the batture area of a small section of the Mississippi River levee with the root extension of the same species along the New Orleans outfall canals. Roots extended significantly longer in the river sediments than in the levee sections for the largest root diameter thresholds (Table 11), but only 101 roots were counted in this size class for these species on 74 root-profile walls. A more direct answer to the question would be available from comparisons of sample root extent of pairs of trees, one growing on a typical urban soil and a twin with roots growing into a levee. While some root-profile walls were excavated at the toe of the levee, we could not make a reliable estimate of the radial extent of larger roots from the base of the tree because of species variation and the relatively high number of trees positioned on the toe of the levee.

Since most of the root-profile walls were excavated within levee sections, soil types encountered were predominantly disturbed soils from a biological perspective: homogenous clay or silt fills with some degree of compaction. Even in river or marine sediments, heterogeneity exists and influences root distribution. Three aspects concerning soils effects on root growth need further study for predicting root behavior near levees: (1) the effect of compaction of homogenized soils; (2) the effect of homogenization; and (3) the effect of soil texture.

Our limited exploration of deep roots on two abandoned levee sections suggests that deep roots are uncommon but do exist. Sampling was limited and necessarily unstructured given their apparent rarity. This is a time-consuming, expensive method for sampling deep roots. While greater exploration may eventually improve the ability to predict the probability of root distribution, geotechnical tests of the effect of large, deep roots on levee integrity is needed to determine the actual risks these roots have on levee failure, especially for trees that die. Construction of a physical model should be possible to explore the effects of root channels on outfall levees. These studies would complement additional field sampling and analysis of the distribution of large tree roots near levees. Given the extreme depths and radial extents that have been reported for tree roots, some degree of root intrusion should be expected from trees on property bordering levees.

Another important question that could not be addressed in this study is how far a tree must be from the levee toe to avoid a tree falling in high winds and the root ball destroying the base of the levee. Intuitively, while the size of the root ball varies inversely with soil moisture, larger trees create larger pits and thus, must be further from the toe to avoid weakening the levee. High wind events create convenient opportunities for collecting data on the diameter and depth of the pit created by windthrown trees as well as species, stem diameter, and the gravimetric soil moisture content of the surrounding soil. Other useful information such as true crown spread and tree height, would be difficult to measure on downed trees since branch angles change when not supporting their own weight.

Predicting the vulnerability of individual trees to windthrow is extremely difficult because tree failure is not a function of mechanical properties of tissue or even individual organs such as stems and branches but a function of the structure and developmental history of the entire tree. For example, stem breakage usually occurs at higher wind speeds than wind throw; consequently, stem breakage is not so much a function of "weak" stemwood but strong root anchorage. Pine trees often break instead of tipping because of tap roots. Stem defects and past injuries create notch stresses that would cause breakage in trees that would otherwise tip. Structural data can only collected on standing trees. Therefore, an inventory of trees on levee right of ways would create a data set that in association with storm-damaged trees could be used to develop a hazard rating system for trees along outfall canals and protection levees. This information would provide quantitative support for removing or leaving trees near levees based on windthrow risk. The i-Tree.org has developed an inventory system for urban trees that could be used as a template for identifying and collecting tree data. i-Tree.org is a cooperative of Federal, state, and private agencies with the goal of assisting urban areas to manage urban forests. The USDA Forest Service hosts a database on tree failures (http://svinetfc2.fs.fed.us/natfdb/). This database currently contains more than

5000 reports of tree failure. It is a source for relevant variables to record on storm-damaged trees and for information of modes of failure for various species and genera.

APPENDIX 1 – Measurement and Sampling Diagrams

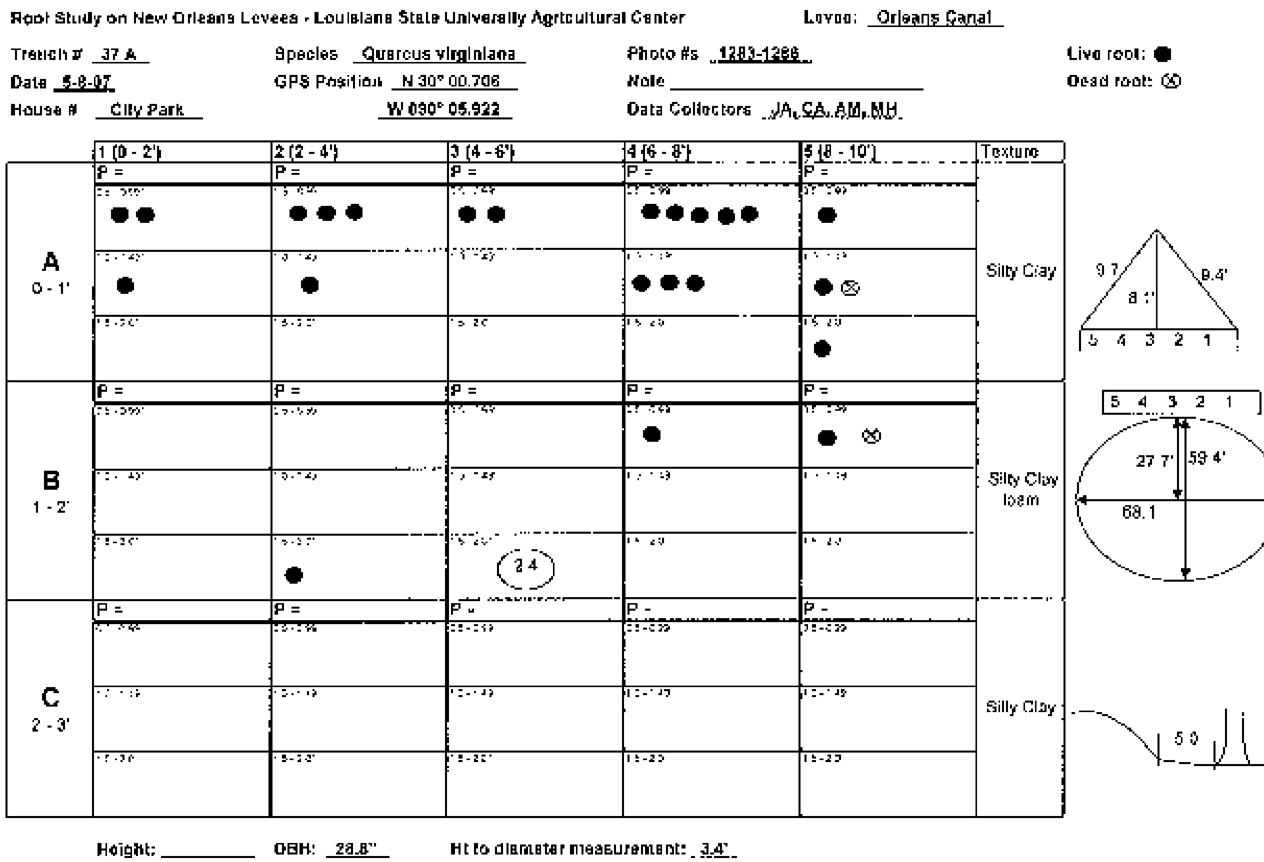


Figure A 1.1. Data sheet for recording characteristics of the tree selected for sampling, the position of the trench relative to the tree and to the toe of the levee, soil texture, and the number of roots protruding through the root-profile wall. The grid for recording roots corresponds to the grid established on the profile wall.

Trenching diagrams - Profile

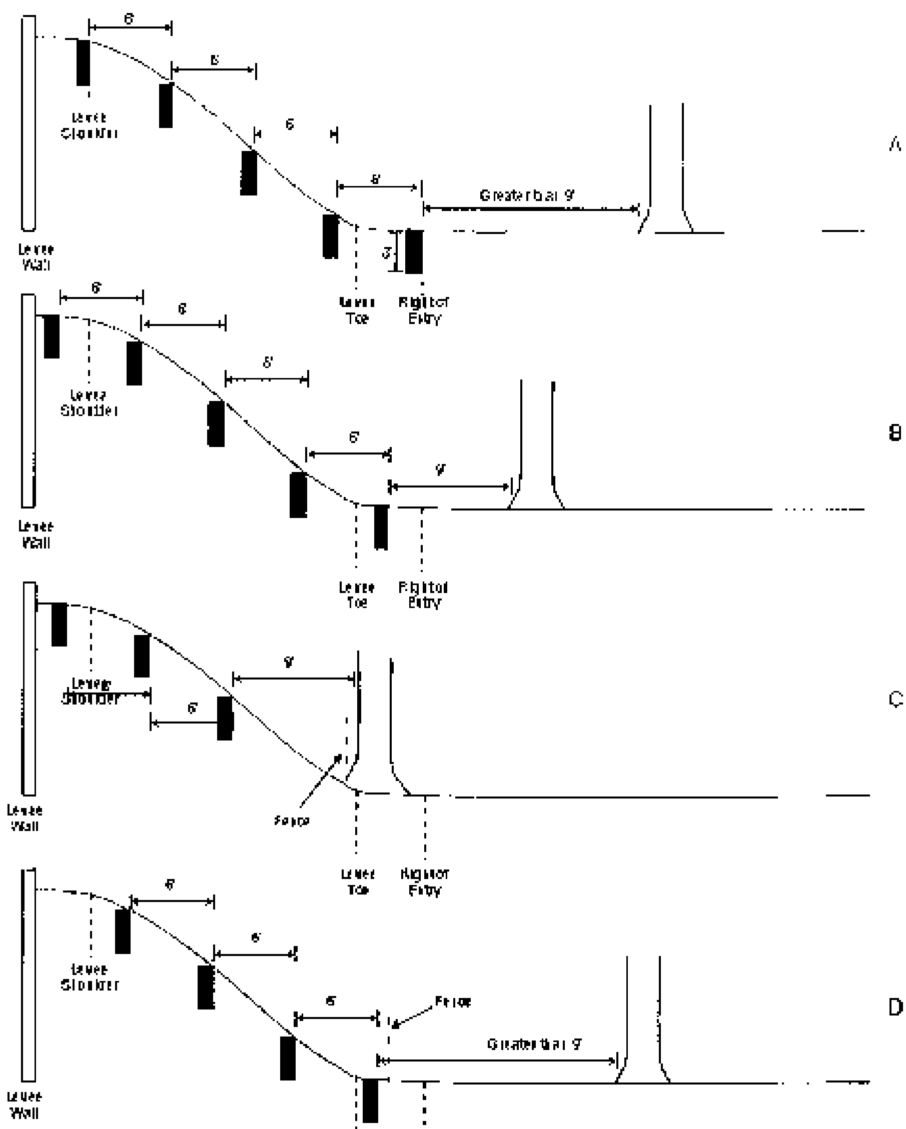


Figure A 1.2 (a-d). Idealized root-wall-profile trench layouts for several measurement scenarios.

A: Scenario A was utilized on the levees of the London St. and the 17th St. outflow canals. We placed the trench directly adjacent to the right of entry and followed with subsequent trenches at 6 foot intervals until few or no roots were found or until we reached 3 feet of the levee wall. The pattern of subsequent trenching is the same after each initial trench regardless of its position.

B: Scenario B occurred on the levees of the London St. and the 17th St. outflow canals. When the tree in question was within 9 feet of the right of entry, we placed the first trench at approximately 9 feet from the stem of the tree.

C: Scenario C was common on the levees of the London St. and the 17th St. outflow canals. Often a fence was erected at the toe of the levee and the subject tree was directly behind the fence. In this situation, we placed the first trench 9 feet away from the stem of the tree.

D: Scenario B occurred on the levees of the London St. and the 17th St. outflow canals. In several cases, the subject tree was located in a yard that had a fence outside the right of entry. In this case, we placed the first trench as close to the fence as possible. If the fence was within 9 feet of the tree, we placed the trench at 9 feet.

Trenching Diagrams – Profile (cont.)

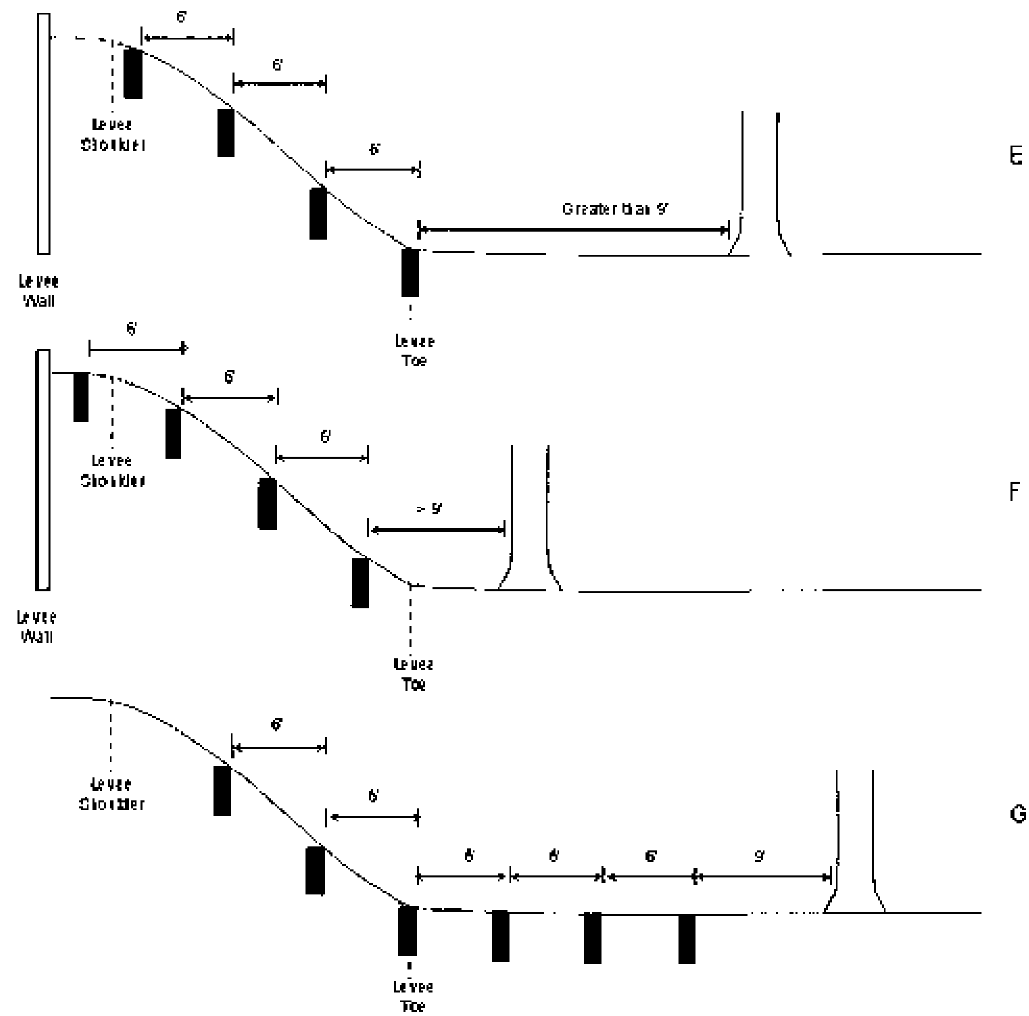


Figure A 1.2 (e-g). Idealized root-wall-profile trench layouts for several measurement scenarios.

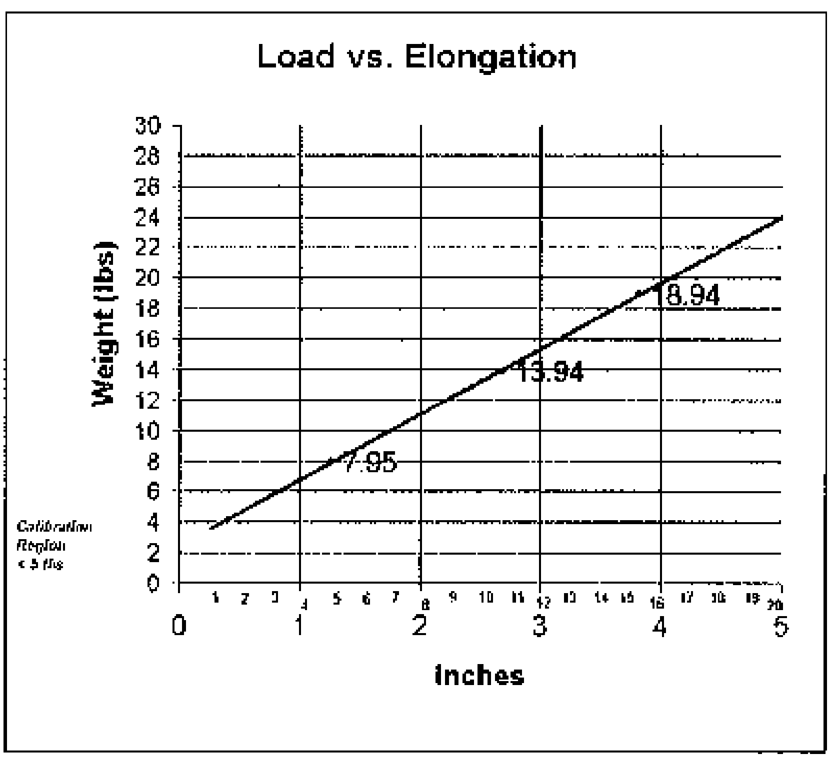
E: Scenario E was generally employed on the levees of the Orleans outflow canal. If the distance from the tree to the toe was greater than 9 feet, we put the first trench at the toe of the levee so that the flat ground of City Park was not disturbed.

F: Scenario F was used at the Orleans outflow canal when the tree in question was within 9 feet of the levee toe. In this case, we placed the first trench 9 feet from the tree.

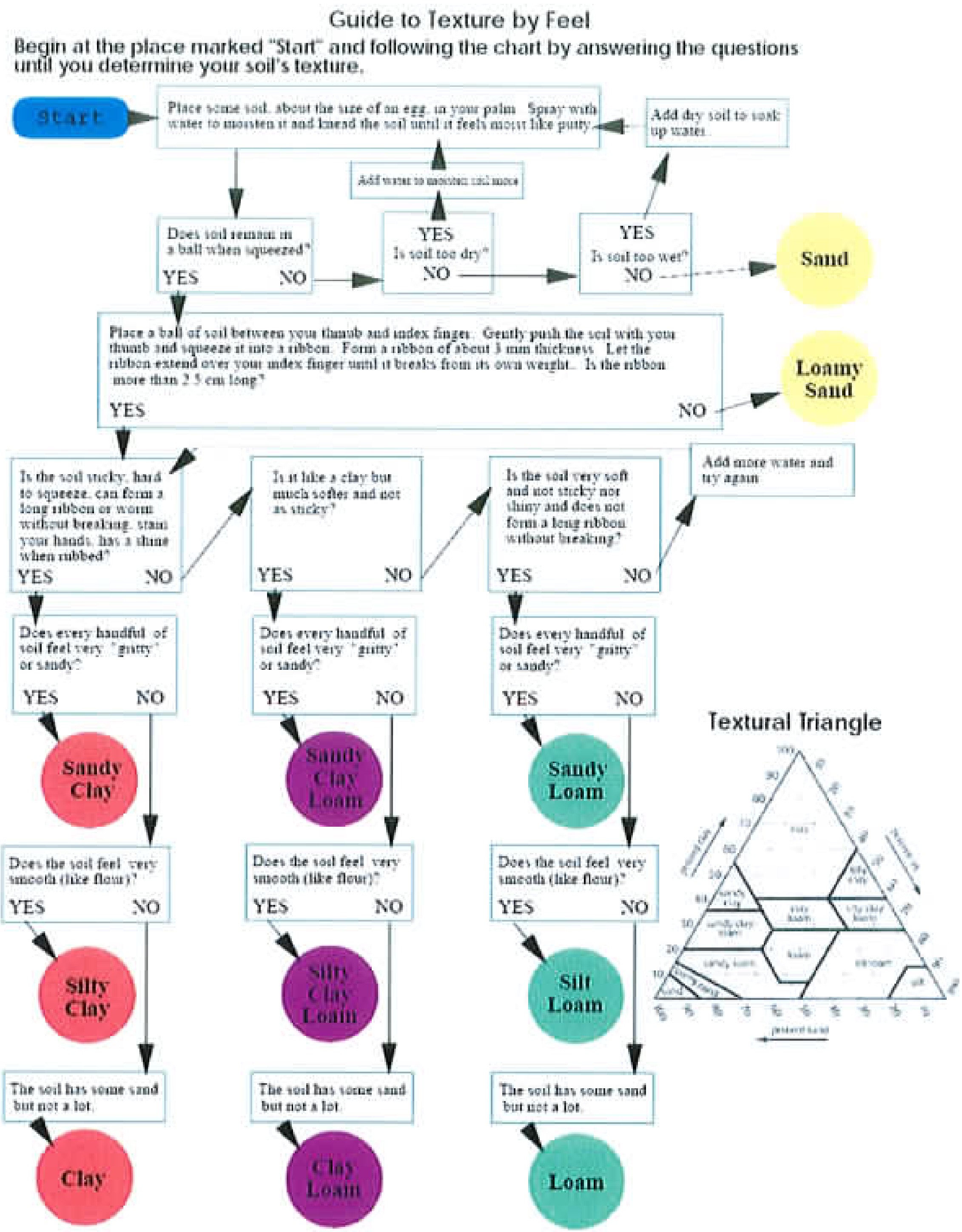
G: Scenario G was commonly found on the Pontchartrain Lakefront and the Old Mississippi River levees. Trees were generally more than 9 feet away from the toe of the levee so the first trench was usually located on flat ground. The roots never extended to the top of the levee in either of these locations.

APPENDIX 2. Published calibration data of Lang penetrometer from http://www.langanalytical.com/Technical%20Data%20Sheet.htm

Scale #	Force-Pounds (lbf)	Comments
1	3.57	non-linear
2	4.64	Begin linear
3	5.72	range
4	6.79	
5	7.86	5.05 is Lower
6	8.94	QC Point
7	10.01	
8	11.09	
9	12.16	
10	13.24	10.72 is Middle
11	14.31	QC Point
12	15.39	
13	16.46	
14	17.54	15.27 is Upper
15	18.61	QC Point
16	19.68	
17	20.76	Linear
18	21.83	Data
19	22.91	
20	23.98	



APPENDIX 3. Decision guide for determining soil texture by feel.



Source: USDA National Resources Conservation Service

Appendix 4. Parameters for 3-parameter Weibull probability density function determined with maximum likelihood for the three root-diameter threshold classes for the species sampled along the New Orleans outfall canals, and the protection levees along the Lake Pontchartrain and a short section along the Mississippi River. These parameters are used for the equation

$$x = b[-\ln(1-P)]^{1/c} + a,$$

where x= the distance from the tree corresponding to the cumulative fraction P of roots counted on a series of root-profile walls at increasing distance from the tree.

Species	>0.5 inches			>1.0 inches			1.5 inches		
	a	b	c	a	b	c	a	b	c
Baldcypress	8.436	3.826	1.196	8.372	3.698	1.202	8.585	3.128	1.023
Live Oak	7.900	5.922	0.010	7.899	3.181	1.003	7.899	2.285	1.004
Pecan	8.200	9.873	0.010	8.200	7.373	1.000	8.199	4.163	0.573
Slash pine	8.097	3.610	1.003	8.098	2.815	1.004	8.084	1.379	1.038
Sugarberry	7.800	3.721	1.002	7.182	4.500	1.477	8.200	4.604	0.010
Sycamore	8.200	8.187	0.010	8.198	6.653	1.002	8.195	4.374	1.005
Tallow	6.630	7.588	1.113	6.677	5.034	1.044	6.693	4.858	1.005
Water oak	7.800	4.409	0.010	7.800	2.577	1.001	7.276	1.000	2.000

APPENDIX 5

ANNOTATED BIBLIOGRAPHY

Appendix 5 – Annotated Bibliography

Abernethy, B. and I. D. Rutherfurd. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes* 15:63-79.

This paper investigates the root systems of two Australian riparian tree species: swamp paperbark (*Melaleuca ericifolia*) and river red gum (*Eucalyptus camaldulensis*). The root density were assessed at each of the sites by mapping the size and location of all roots intersected by a number of vertical profile walls dug at various distances between the tree trunks and the canopy driplines. Variations in root density were assessed at each of the sites by mapping the size and location of all roots intersected by a number of vertical profile walls. The walls were dug at various distances between the tree trunks and the canopy driplines. Details on how the roots were classed and mapped were described further in section of root distribution. Root area ratio (RAR), relationship between root diameter and root strength, and between root diameter and root tensile strength were discussed. The reinforcement drops off very quickly with depth and with distance from the tree. The interspecies differences in the strength of living roots have less significance for bank reinforcement than interspecies differences in root distribution.

Barton, C.V.M. and K.D. Montagu. 2004. Detection of tree roots and determination of root diameters by ground penetrating radar under optimal conditions. *Tree Physiology.* 24:1323–1331.

Tested the ability of GPR with 500MHz, 800 MHz, and 1 GHz antennas to detect roots and root sizes of buried root samples. Root samples were buried at zero to 3.9 inches (10 cm), 19.5 inches (50 cm) and 5.9 to 1550 inches (15 to 155 cm). The 800 MHz samples produced the best results. Roots as small as 0.39 inches (1.0 cm) could be detected as the root mean squared error of prediction equations were .24 inches (0.6 cm). Only scans perpendicular to roots give quality data. Needed hyperbola of signal reflections are not made for roots parallel to the scan and those not perpendicular produce distorted hyperbolas. High clay, high water content and salt containing soils attenuate the signals rapidly so detection on limited to near the surface (depths of less than 3.2 ft (1 m)). The authors indicate that closely spaced roots as with tree root systems produce confusing profile results as interactions of hyperbolas from each target are produced. Signal conditioning and software can remove some problems, but are still not affective for many applications. Signal strength is confounded by depth and cannot be used alone determining root diameter. Waveform parameters could be used to detect root diameters of roots accurately when scanned at right angles to the roots, in uniform dry sandy soils to a depth of 4.9 ft (1.5 m).

Batey, T. and D. C McKenzie. 2006. Soil compaction: identification directly in the field. ***Soil Use and Management.*** **22:123-131.**

It is interesting that one section "patterns of root development" in this paper discussed how roots react when they meet compacted soil. Roots growing in a compact layer are often much thicker and distorted on appearance, intend to run horizontally, and so on. In subsoils of sand, root penetration may be restricted to no more than 3.1 to 3.9 inches (8-10 cm). The roots appeared swollen.

Berry Allison 2007. Trees and levees: How and where do tree roots grow? Vegetation challenge symposium. Sacramento, California August 28, 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm

The presentation provided an introduction to basic tree root behavior and some of the anomalies that occur. It also reported on recent and ongoing investigation of tree roots in the Central Valley of California. The speaker contrasted the root character of cottonwood, Douglas-fir, and valley oaks. In a study at Mayhew in Sacramento the author began an investigation on tree roots in levees. The work presented related to three mature oaks with one used as the representative for the others. The author used the root wall profile method of mapping roots. The L-shaped trench was 48 ft (14.6 m) long, 4 ft (1.2 m) deep and approximately 14 ft (4.2) from the trunk of the tree. Roots were dotted on acetate sheet and sizes were recorded. Roots were not found when soil bulk densities exceeded 101.8 lb/ft3 (1.63 g/cm3) in a sandy loam soil. Most roots measured in root wall profile technique were in the upper 2 ft (.6 m) of soil. Few roots were found between 2 and 4 ft (.6 - 1.2 m) of depth. Ground penetrating radar was used to search for roots deeper than 4 ft (1.2 m). Initial data indicated large roots, those greater than 1 inch (2.54 cm) in diameter, occurred at depths of 4 to 6 ft (.6 – 1.2m). The author suggested some roots may be growing beneath the levee. One actual sample, below 4 ft (1.2 m), revealed roots in the 4 to 6 foot depth (.6 – 1.2m).

Bischetti, G.B., E.A. Chiaradia, T. Simonato, B. Speziali, B. Vitali, P Vullo and A. Zocco. 2005. Root strength and root area ratio of forest species in Lombardy (Northern Italy). ***Plant and Soil.*** **278:11-22.**

This paper presents a synthesis of the data gathered in the last five years for some species in different locations of the Alps and preAlps of Lombardy (Northern Italy). The objective was to test root tensile strength and Root Area Ratio (RAR) distribution within the soil for various species and compare the findings with past research. Tensile strength tests were carried out for eight species (green alder, goat willow, red willow, beech, hazel, European ash, Norway spruce and European larch). Live roots of these species were gathered and tensile tests were carried out within one week. If more than a week elapsed, one of three options was used. The roots would be dried then reconstituted with water, frozen in water, or dried and reconstituted with alcohol. Only roots 0.19 inches (5 mm) or less could be used as larger roots either broke at the point of the clamp or slipped through. Tensile strength was calculated by dividing the peak load by the cross-sectional area of the root European larch *(Larix decidua),* hazel *(Corylus avellana)* and European beech, (*Fagus sylvatica)* had the highest mean tensile strength and European ash (*Fraxinus excelsa)* and green alder (*Alnus viridis)* had the lowest. Root Area Ratios were as expected: they decreased with increasing soil depth. In most cases the maximum RAR values were located in the first 11.7 inches (30 cm) and the maximum depth is about 3.2 ft (1 m). These results confirm what has been reported to date. Comparing tensile strength for beech and Norway spruce, it seems that environment does not significantly affect tensile strength – a contrast to past research. The paper continues on to discuss specific tree root tensile strength in more detail.

Bolte, A., T. Rahmann, M. Kuhr, P. Pogoda, D. Murach and K.V. Gadow. 2004. Relationships between tree dimension and coarse root biomass in mixed stands of European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* [L.] Karst.). *Plant and Soil.* 264: 1-11.
Relationships between tree parameters above ground and the biomass of the coarse root system were examined in six mixed spruce-beech stands. Coarse roots (d greater than or equal to 0.078 inches (2 mm)) of 42 spruce and 27 beech trees were sampled by excavating the entire root system. The length and radius of every coarse root were measured. A framework for recording coarse root dimensions was discussed. The R^2 show strong relationships between the coarse root biomass (CRB, dry weight) and the corresponding tree diameter at breast height (DBH) (R^2 =0.92 for spruce and 0.94 for beech). Site conditions of varying climate and soils and interspecific tree competition are likely to affect root/shoot ratio and DBH-coarse root biomass relationships.

Brooks, J.R., F.C. Meinzer, R. Coulombe and J. Gregg. 2002. Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. *Tree Physiology.* 22:1107-1117.
Study of the hydraulic redistribution of soil water suggests roots are able to bring water from more than 6.5 ft (2 m) depth to the soil above for use by trees and other plants during dry periods. Hydraulic redistribution was measured in both Douglas-fir and Ponderosa Pine. Although root system depth was known to exceed 4.9 ft (1.5 m), root system depth was not measured. A partial excavation of root systems of several trees indicated numerous woody sinker roots extending to depths greater than 4.9 ft (1.5 m). Numerous similar studies from around the world could be interpreted to suggest similar hydraulic redistribution results for a large number of species. Authors indicated that at the time of publication, more than 60 reports of hydraulic redistribution had been published.

Brown J.H., and F.W. Woods. 1968. Root extension of trees in surface soils of the North Carolina Piedmont. *Botanical Gazette.* 129(2):126-132.
This study involved treating the soil with radioiodine in a carrier solution and monitoring the uptake by the roots and stems to determine how far tree roots extended. A total of 703 stems were studied and species were grouped as: sourwood, dogwood, red cedar, hickories (all *Carya* spp.) white oaks (*Q. alba* and

Q. stellata), and black oaks (*Quercus* species: black oak (*velutina*), southern red oak *(falcate)*, scarlet oak *(coccinea)*, red oak *(rubra)* and blackjack oak (*marilandica*)). Upon conclusion, the authors found that white oak roots are able to pull-in solution from greater distances and at a higher percentage (percent of trees that took up radioiodine). Around 98 percent of the trees showed signs of radioiodine from roots 15 ft (4.5 m) from the trunk. Dogwood showed the shortest distance and percentage and all others were fairly even. There was a significant drop-off in the percent of trees showing uptake at around 15 ft (4.5 m). Maximum distance of recorded uptake (root length) ranged from 31.8 ft (9.7 m) for dogwood, 33.3 ft (10.1 m) for red cedar to 31.6 ft (9.6 m) for hickory. Maximum distances for the white oak and black oak groups were 38.1ft (11.6 m) and 11.7 ft (3.5 m), respectively.

Burgess, S.O., M. Adams, N. Turner and C. Ong. 1998. The redistribution of soil water by tree root systems. *Oecologia*. 115:306-311.
This article examines the process of hydraulic redistribution of water by tree roots both upward in dry conditions and downward in wet conditions. The authors calculated root sap flow using a modified heat pulse method to determine the level of redistribution in both silk oak (*Grevillea robusta)* and river redgum (*Eucalyptus camaldulensis)*. Before rain, rates of flow in lateral roots of silk oak (*G. robust)a* were negative indicating that water was moving away from the stem base toward the root tip. This happened only at night and during times of low transpiration. After rain, sap flow was positive, indicating that water was taken up from the surface layers. The data strongly supports the hypothesis that water is redistributed either up or down whenever the water potential of roots is unequal.

Burgess, S.S.O. and T.M. Bleby. 2006. Redistribution of soil water by lateral roots mediated by stem tissues. *Journal of Experimental Botany*. 57(12):3283–3291.
Roots redistribute soil water through the process of hydraulic lift or hydraulic redistribution. Study was designed to elucidate the soil water redistribution and flow pathways. The area of study was in western Australia and soils were of sandy loam to clay loam texture. Primary species were salmon gum (*Eucalyptus salmonophloia*) and eucalyptus wandoo (*E. wandoo*). Substantial and rapid hydraulic redistribution occurred among roots after rains, suggesting transfer of water among roots at different depths. The importance of this information is in the withdrawal of water from soil of different depths and the transfer of water to other soil zones. The transfer of water among roots suggests aid in root growth and survival during water shortages within the soil profile.

Burgess, S.O., J.S. Pate, M.A. Adams and T.E. Dawson. 2000. Seasonal water acquisition and redistribution in the Australian woody phreatophyte, *Banksia prionotes*. *Annals of Botany* 85:215–224.
Study examined hydraulic lift during the dry season for the species acorn banksia or orange banksia (*Banksia prianotes)*. Authors suggested that extremely dry soils may limit the theory of hydraulic lift especially in soils were seasonal changes

affected soil moisture. By using dye injections and a "heat ratio" method, the investigators were able to demonstrate the reversible flow of xylem sap in lateral roots and also the outward flow of water from the fine feeding roots of *Banksia prionotes*. The study strongly suggested that lateral roots of the species studied could both absorb and exude water in response to gradients in water potential between root and soils. Data also suggested that dry conditions would reduce the amount of water lost from this species' roots either due to the mortality of fine roots or hydraulic discontinuity in the soil matrix but would not completely stop water loss.

Butnor, J. R., J.A. Doolittle, L. Kress, S. Cohen, and K.H. Johnsen. 2001. Use of ground-penetrating radar to study tree roots in the southeastern United States. *Tree Physiology*. 21:1269–1278.

The study tested the use of ground penetrating radar (GPR) to examine root distribution in several forested areas including southern Piedmont, Carolina sandhills and Atlantic coast flatwoods. Tests of antenna of 400 MHz versus 1.5 GHz were also included. GPR performed well on sandy soils with roots perpendicular to the scan sweep (r^2 =0.55), but were not adequate in clay soils, excessively wet soils, soils with obstructions of various sizes, when roots were touching or in close proximity to one another, and when roots were not perpendicular to the scanning radar. Uneven surface soil also presented problems. Results were reported for depths ranging from 0 to 7.8 inches and 7.8 to 15.6 inch (0 to 20 cm and 20 to 40 cm) depths. Water tables severely distort root signals and roots are missed. Live roots could be detected to less than 0.2 inches (0.5 cm) in diameter, but dead and decaying roots less than 0.2 inches (5 cm) in diameter went undetected. Root detection in heavy clay soils was poor and inclusions of coarse fragments were easily mistaken for tree roots. Similar results were reported for soils with coarse rock fragments. The lower MHz antenna provided a better picture of roots above 1.4 inches (3.7 cm), but smaller roots went undetected. Correlations to root diameter generally decline with depth. According to the authors, soils with high electrical conductivity dissipate the radar and severely restrict observation depths. Clay content also decreases signal strength and detection depth limits.

Butnor, J.R., J.A. Doolittle, K.H. Johnsen, L. Samuelson, T. Stokes and L. Kress. 2003. Utility of ground-penetrating radar as a root biomass survey tool in forest systems. *Soil Science Society of American Journal*. 67:1607-1615.

This study was conducted in a 5-year old loblolly pine (*Pinus taeda)* plantation on uniform soils of a loamy sandy and loamy texture that were well drained to excessively well drained. Under these nearly perfect conditions; Ground Penetrating Radar (GPR) was used to depict root volume of roots at the mid-point between trees in each row sampled. Thus the majority of roots were perpendicular to scans. Scanning occurred in control blocks, irrigated blocks and fertilized blocks. After background noise removal and data transformation, good agreement was reached between GPR data and root data from soil cores. Corrections were necessary in the fertilized plots, since root volume was much enhanced. The authors stress the need to calibrate for each soil condition even when the soils are similar, and the necessity of uniform site conditions. Fertilization significantly impacted the amplitude of the scan signals. Greater dissipation of signals reduces accuracy or depth of scanning, but in this study, roots were only scanned to 11.7 inches (30 cm). Four hours of scanning could produce 1000 linear feet (305 m) of scanned area in a narrow strip. Successful scanning required an even surface with no more than pine needles as disruption.

Caldwell, M. M., T. E. Dawson and J. H. Richards. 1998. Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia*.(1998) 113:151-161.

Abstract: Hydraulic lift is the passive movement of water from roots into soil layers with lower water potential, while other parts of the root system in moister soil layers, usually at depth, are absorbing water. Here, we review the brief history of laboratory and field evidence supporting this phenomenon and discuss some of the consequences of this below-ground behavior for the ecology of plants. Hydraulic lift has been shown in a relatively small number of species (27 species of herbs, grasses, shrubs, and trees), but there is no fundamental reason why it should not be more common as long as active root systems are spanning a gradient in soil water potential (ψ_s) and that the resistance to water loss from roots is low. While the majority of documented cases of hydraulic lift in the field are for semiarid and arid land species inhabiting desert and steppe environments, recent studies indicate that hydraulic lift is not restricted to these species or regions. Large quantities of water, amounting to an appreciable fraction of daily transpiration, are lifted at night. This temporary partial rehydration of upper soil layers provides a source of water, along with soil moisture deeper in the profile, for transpiration the following day and, under conditions of high atmospheric demand, can substantially facilitate water movement through the soil-plant-atmosphere system. Release of water into the upper soil layers has been shown to afford the opportunity for neighboring plants to utilize this source of water. Also, because soils tend to dry from the surface downward and nutrients are usually most plentiful in the upper soil layers, lifted water may provide moisture that facilitates favorable biogeochemical conditions for enhancing mineral nutrient availability, microbial processes, and the acquisition of nutrients by roots. Hydraulic lift may also prolong or enhance fine-root activity by keeping them hydrated. Such indirect benefits of hydraulic lift may have been the primary selective force in the evolution of this process. Alternatively, hydraulic lift may simply be the consequence of roots not possessing true rectifying properties (i.e., roots are leaky to water). Finally, the direction of water movement may also be downward or horizontal if the prevailing ψ_s gradient so dictates, i.e., inverse, or lateral, hydraulic lift Such downward movement through the root system may allow growth of roots in otherwise dry soil at depth, permitting the establishment of many phreatophytic species.

Campbell, K. A. and C. D. B Hawkins. 2003. Paper birch and lodgepole pine root reinforcement in coarse-, medium-, and fine-textured soils. *Can J Forest Res.* 33:1580-1586.

Root reinforcement is affected by soil physical properties. Removal of vegetation reduces slope shear resistance, and may cause mass failure. This paper compared the contribution of paper birch (*Betula papyrifera* Marsh.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) roots to soil resistance. A sonotube experiment included six birch, one pine population, and a control (no trees planted), The tubes were filled with coarse-, medium-, and fine-textured soils. Five trees per tube were planted for each species. A shear device was built. Results showed roots of paper birch and lodgepole pine trees contributed to a significant increase in soil shear resistance, regardless of soil type. At a shear depth of 0.65 to 1.44 ft (0.20 to 0.44 m), paper birch contributed greater reinforcement than lodgepole pine. Both birch and pine provided the most root reinforcement in coarse-textured soil and the least reinforcement in medium-textured silt soil.

Canadell, J., R.B. Jackson, J.B. Ehleringer, H.A. Mooney, O.E. Sala, and E.D. Schulze. 1996. Maximum rooting depth of vegetation type at the global scale. *Oecologia.* 108:583-595.

This article summarizes maximum rooting depths of species belonging to major terrestrial biomes (boreal forests, croplands, desert, sclerophyllous shrubland, temperate coniferous forest, temperate deciduous forest, temperate grassland, tropical deciduous forest, tropical evergreen forest, tropical grassland/savanna, and tundra). A total of 290 observations were compiled containing 253 different plant species, 194 of which had roots at least 6.5 ft (2 m) deep, 50 had roots of 16.4 ft (5 m) or more and 22 had roots 32.8 ft (10 m) or more. Desert plants produce very deep roots allowing them to tap into deep water sources. Overall, trees produce the deepest roots followed by shrubs, herbaceous plants and then crops. The maximum rooting depth of each of the biomes was as follows: Boreal forest – 10.8 ft (3.3 m) by lodgepole pine, (*Pinus contorta)*; Crops 12.1 ft (3.7 m) by alfalfa (*Medicago sativa)*; Desert – 173.8 ft (53 m) by mesquite (*Prosopis juliflora)*; Sclerophyllous shrubland and forest – 43.3 ft (13.2 m) by shrub Laurel sumac (*Rhus laurina)* and 131.2 ft (40 m) by tree Jarrah (*Eucalyptus marginata)*; Temperate coniferous forest – 24.6 ft (7.5 m) by Allepo pine (*Pinus halepensis)*; Temperate deciduous forest – 14.4 ft (4.4 m) by Bur oak (*Quercus macrocarpa)*; Temperate grassland – 20.6 ft (6.3 m) by both forage kochia (*Kochia prostrate)* and rush skeletonplant (*Lygodesmia juncea)*; Tropical deciduous forest – 15.4 ft (4.7 m) by kuayun (*Gironniera subaequalis)*; Tropical evergreen forest – 59 ft (18 m) by Shepard's tree (*Boscia albitrunca)*; Tundra 2.9 ft (0.9 m) by diamond-leaf willow (*Salix planifolia)*. Tundra plants are limited by permafrost.community; Tropical grassland and savanna – 223 ft (68 m) by shepard's tree (*Boscia albitrunca)*; Tundra - 9 meters by diamondleaf willow (*Salix planifolia)*. Tundra plants are limited by permafrost.

Clinton B. D. and C.R. Baker. 2000. Catastrophic windthrow in the southern Appalachians: Characteristics of pits and mounds and initial vegetation responses. Forest Ecology and Management. 126:51-60.
A summary and characterization of pit and mounds produced by 14 species of trees blown over during catastrophic winds is presented for the Coweeta Basin in western North Carolina. Most damage occurred at upper slope and ridge tops. These positions contained larger trees with full crowns. Pit and mound characteristic (root ball size) were not related to tree size or species, but were generally larger in shallow soils and saturated soils.

Coder, K.D. 1998. Root growth control: managing perceptions and reality. The landscape below ground II. In (*ed.*) Neely, D. and G. Watson. *Proceedings of a second international workshop on tree root development in urban soils.* International Society of Arboriculture. pp 51-81.
This is a review paper concentrating on some of the misperceptions related to tree root damage brought about by flaws in engineering. The paper presents an important summary of what is known about root growth in urban environments and presents some information on resolutions. It covers general principles of root growth, growth mechanics, growth forces, and changes that occur as soil environment changes. Some of these conditions are related to the building of structures and the relationships to trees commonly occurring in developed environments, but the paper misses some nuances associated with tree species that can handle certain extremes, such as, permanent or near constant flooding. However, taken in this context, the information is still useful. The most useful part of this paper is the review of methods for controlling root growth. Outside of "tree-literate" design and avoidance of putting trees near structures, the author provides a discussion of six methods of root growth control. The best of these methods is the inclusion of large air gaps. Root growth is prevented by building supporting stone matrices with large air spaces, instead of fine materials, which makes area surrounding the stone extremely well-drained and impermeable to root penetration. Two-dimensional barriers are also mentioned, the plus being that they are commercially available. The downside to these barriers is that some roots always manage to get past the barriers. If most cases, these barriers are only 12 to 24 inches deep (30 – 61 cm), but are also available in depths to 60 inches (152 cm). Most problems with barriers is the root egress. Egress can occur over the top of the barrier when damage to the barrier occurs (frequent); or roots commonly are forced down below barriers only to grow back toward the surface once they exit below the barrier. Roots can also grow through cracks (made during installation) in the barriers. Traps, deflectors, and inhibitors can be part of the barriers; each of these has its own strengths and weaknesses. Placement of barriers away from existing trees and roots is essential to improving their success. The remaining types of root control systems were normally less effective.

Corcoran, M.K., P. Bailey, C. Little, and F.Pinkard. 2007. Literature review and preliminary assessment. Vegetation challenge symposium. Sacramento,

California August 28, 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm
The presentation provided the methodology used for a literature review on vegetation effects on levees. The objectives of the literature review were to summarize the pertinent literature and identify data gaps. The literature review was to include wider array of documents than those contained just in the refereed journal literature and included all types of vegetation and international literature. Literature review is not cited in the materials available, but speaker did indicate that about 140 papers were included in the literature review and 18 of those dealt with vegetation on levees. Of those, eight appeared to be on the same research but published in multiple outlets.

Coutts, M. P., 1983. Root architecture and tree stability. *Plant and Soil* 71:171-188.
Root anchorage is discussed by applying lateral forces to Sitka spruce root systems with a winch to pull the tree over. Field measurements included the applied force, angles of inclination, soil and root movement, timing of the sound of root breakage using buried microphones, weight and shape of the root-soil plate, damage to the roots, dimensions and mass of the root-soil plate levered from the ground by the displaced stem, tensile strength of roots and soil beneath the plate, root and soil tensile strength, root/soil resistance on the windward perimeter, and (on the leeside) the stiffness of the hinge at the fulcrum. Strength properties of roots and soil are reviewed. Results showed the leeside of the root-soil plate acted as a cantilevered beam and determines the distance of the fulcrum from the tree. On the windward side, upward movement of the root-soil plate causes sequential breakage of soil and roots. Under an increasingly applied load, failure occurs in parts of the soil-root system before the maximum force for uprooting is achieved.

Coutts, M. P., 1987. Developmental processes in tree root systems. *Canadian Journal of Forest Resources* 17:761-767.
This paper reviewed factors that influence the primary and secondary growth of roots in terms of the development of the form of tree root systems. The primary root growth is the development of the seedling radical and lateral roots of primary structure. The secondary growth is the development of woody root system. In trees, the local environment has some direct effects on the root cambium, but such effects appear to be less important than the activity of the roots of primary structure. The review discussed root development from the aspect of plant physiology.

Coutts, M.P. 2004. Eco-engineering and conservation of slopes for long-term protection from erosion, landslides and storms. *Quality of Life and Management of Living Resources. 5.3.1 Multifunctional Management of Forests. Eco-Slopes: Final report.* QLK5-CT-2001-00289. 26 November 2004.
This study was part of a multidisciplinary project to determine influence of vegetation on slope stability. The study covered many aspects of tree roots, including architecture, topology, tensile strength, soil and hydrological interactions. Also covered was a large number of species and slope conditions and susceptibility of windfall. The study indicated that trees growing on slopes are more resistant to overturning than trees on flat terrain. This paper summarized much of the available literature. A "Slopes Decision Support System" was developed for use by foresters, engineers and ecologists to manage planting and species choice for slopes with instability problems. Species vary widely with respect to tolerating of handling various types of physical stress. A species that handles one kind of physical stress well may not handle others as well. Testing is necessary to verify resistance or tolerance to various kind of physical stress. The most common way to test trees against stem failure of uprooting is to winch trees sideways until failure. Species with deep, wide-spreading roots tend to resist windthrow the best. However, soil root interactions are important and can alter the effects tremendously. Well anchored species on one soil type may become susceptible on another. Tree roots help bind soils and anchor the soil reducing erosion and landslide, but the overturning of trees can actually have a negative impact and is often described as the critical factor in landslides. The paper describes a large scale study of measurement and modeling of the effects of trees (forests) and soils on slope stability. Many aspects of different models were considered and used to develop the SDSS expert system model.

Coutts, M. P. and G. J. Lewis. 1983. When Is the structural root-system determined in Sitka spruce? *Plant and Soil* 71:155-160.
Growth ring analysis of root systems of Sitka spruce trees showed that the radial growth took place mainly during the first eight years. The roots established during this period of time constituted the main structural root system for the spruce trees at stand age 34 years (the highest age of the tested tree). Many of the minor roots stopped growing in diameter after a few years, but were still alive and extending at 34 years.

Coutts, M.P. and B.C. Nicoll. 1991. Orientation of the lateral roots of trees. 1. Upward growth of surface roots and deflection near the soil surface. *New Phytologist.* 119:227-234.
The surface roots grow from the upper part of the tap root, extend for many feet within about 7.8 inches (20 cm) of the ground surface. They are the major structural members of the root system for support and anchorage. This paper described the origin and behavior of the surface roots of lodgepole pine and Sitka spruce. Seeds of the trees were sown in the pots in growth rooms and glass rooms, and the development of surface roots were observed and measured. The authors

concluded that the direction of growth of surface roots is the result of two opposing influences. Specific main lateral roots are plagiogravitropic and grow obliquely upwards, but as these roots approach the soil surface they respond to some signal from the environment that causes downward deflection. The growth behavior described enables the main lateral roots to explore the nutrient-rich surface layers of the soil while avoiding the injury to the root tip that would result from exposure.

Coutts, M.P., C.C.N. Nielsen and B.C. Nicoll. 1999. The development of symmetry, rigidity and anchorage in the structural root system of conifers. *Plant and Soil.* 217:1-15.

The radial symmetry of the woody root system is especially important for tree stability. Internal factors such as the production of root tips capable of forming structural roots, environmental factors including mineral nutrition, and the interactions of the factors control the development of a tree root system. This paper collected information on root system architecture and growth of Sitka spruce for modeling root system development with respect to symmetry and rigidity. The root system is represented as a set of spokes that are variable in number, size and radial distribution. Rigidity varies between and along each of the spokes. The proportion of the total cross section area of the woody roots increased with the decreasing of the root sizes. A diagram summarized the development of the structural root system in response to internal and external factors, which were as: environment, allocation, and seedling physiology.

Crook, M.J. and A.R. Ennos. 1996. The anchorage mechanics of deep rooted larch, *Larix europea X L. japonica. Journal of Experimental Botany.* 47(303):1509-1517.

This is a study of deep-rooted 16-year old larch trees (*Larix europea x japonica*) planted in sandy clay loam soil. Several trees, similar in size, were pulled over with a winch to examine whether the roots broke, or for other signs that they had failed mechanically. Roots were categorized as a windthrow root (any root emerging from the trunk on the counter-winchward side of the tree), a leeward root (any root emerging from the trunk on the winchward side of the tree) or a side root (any root that emerged from the trunk on neither the windward nor the leeward sides). Damage to these roots was recorded, noting the location of each. As the trees were pulled over, several observations were made. The leeward lateral bent, pushed into the soil and at 30-35 degrees, it broke towards its base. In two of three trees, the tap root broke off while in the third, it simply rotated. Anchorage is similar regardless of soil moisture but failure occurs closer to the trunk when it is wet. Similar patterns were observed on subsequent trees.

Crook, M.J. and A.R. Ennos. 1998. The increase in anchorage with tree size of the tropical tap rooted tree *Mallotus wrayi*, King (Euphorbiaceae). *Annals of Botany*. 82: 291-296.

This study tests the theory that for freestanding upright plants the anchorage strength should also increase or scale with the third power of the trunk diameter. *Mallotus wrayi* (no common name available, species found in peninsular Malaysia, Sumatra and Borneo) was chosen because it has a simple tap root system. Thirty-five trees, ranging from 1.6 to 5.6 inches (4.2 to 14.3 cm) in diameter at breast height (DBH) were tested in the clay soils of the Malaysian rainforest. Trees were winched slowly and loads were recorded until the tree leaned by approximately 50 degrees from vertical. After the tests, the root systems were excavated and cleared of soil. Average tap root length and diameter were measured and the tap root was examined after each test to see whether it had been damaged. Failure occurred in one of two ways: either as an anchorage failure, or the trunks broke. Trees that failed remained leaning after the winching but those that did not fail returned to their upright position. The largest trees failed and the smallest did not. Tests showed that bigger trees were better anchored and most big trees failed at the trunk rather than the roots. The largest trees however had stronger stems and caused anchorage failure. Younger trees had more flexible trunks preventing them from breaking or uprooting. None of the trees that were pulled over showed signs of damage to the tap root.

Crook, M.J., A.R. Ennos and J.R. Banks. 1997. The function of buttress roots: a comparative study of the anchorage systems of buttressed (*Aglaia* and *Nephelium ramboutan* species) and non-buttressed (*Mallotus wrayi*) tropical trees. *Journal of Experimental Botany*. 48 (314):1703-1716.

This study compared the anchorage mechanics of buttressed to non-buttressed trees with a series of tests. Species studied were Aglaia (genus Mahogany), *Nephelium ramboutan* (common name pulasan, native to southeast Asia) and *Mallotus wrayi* (no common name available, native to peninsular Malaysia, Sumatra and Borneo). The theory that buttress roots serve as anchorage to buttressed trees was being tested with simulated windthrow tests. Twelve buttressed and fourteen non-buttressed trees were cut down at 9.8 ft (3 m) above the ground. All of the buttressed trees and five of the non-buttressed trees were fixed with strain gauges along the lateral roots and then very slowly winched over. Damage to the trunk and root systems were recorded, noting the extent of any delamination of the wood, together with the position along the lateral of any break, and the height and width of the root at the break. Both buttressed and non-buttressed trees produced a single tap root directly under the bole, but the non-buttressed trees produced more lateral roots than the buttressed trees. The non-buttressed lateral roots were round while the buttressed roots were up to eight times higher than wide – a rectangular cross-section. Only the buttressed trees produced sinker roots. The windward buttress of buttressed trees without sinker roots pulled out of the ground and, eventually, the leeward buttress snapped and the tap root was either pulled from the ground or broken off. The windward buttress of the buttressed trees with sinker roots remained secure in the ground despite winching. The leeward buttress root broke after continued winching, but instead of the windward buttress pulling out of the ground, it split and continued to delaminate. Non-buttressed trees subjected to the same winching showed root movement with leeward laterals buckling, windward laterals uprooting and the tap root pushing into the soil, increasing the size of the crevice left by the tap root. Two interesting findings were: first, the majority of the buttress roots did not have sinkers and second, that buttressed trees did have tap roots. Buttressed trees were twice as well anchored.

Danjon, F., D. Bert, C. Godin, and P. Trichet. 1999a. Structural root architecture of 5-year-old *Pinus pinaster* measured by 3-D digitizing and analyzed with AMAPod. *Plant and Soil.* 217. 49-63.

This study was done to determine the root structure of 5 year old maritime pine (*Pinus pinaster)*, a high yielding forest tree, making up ¼ of the marketed timber in France. The article's abstract provides a thorough explanation of the study – Above and below ground architecture and biomass as well as stem straightness were measured on 29 trees uprooted with a lumbering crane. The geometry and topology of the roots was gained using a low magnetic field digitizing device. Data were analyzed with AMAPmod software. Root number, length, diameter, volume, spatial position, ramification order, branching angle and inter-laterals length were extracted. The proportion of root volume in the zone of rapid taper was negatively correlated with the proportion or foot volume in the tap root indicating compensation between tap root and main lateral root volume. Among all root characteristics, the maximal rooting depth, the proportion of deep roots and the root partitioning coefficient were correlated with the stem straightness.

Danjon, F., H. Sinoquet, C. Godin, F. Colin and M. Drexhange. 1999b. Characterization of structural tree root architecture using 3D digitizing and AMAPmod software. *Plant and Soil.* 211. 241-258.

The purpose of this study was to test a new 3D digitizing method for studying structural root systems using AMAPmod software specifically designed for handling plant architecture. The first method involved excavating the root systems of three, 20-28-year-old sessile oak (*Quercus petrae)* trees in Champenoux Forest in north-east France then 218 five-year-old maritime pine (*Pinus pinaster)* trees in Landes Forest in south-west France. The position coordinates of roots were measured with a 3D digitizer using low frequency electromagnet field sensing. This device measures the special co-ordinates within a sphere of a 13.1 foot (4 m) radius around the emitter. Several root characteristics became available including length, base diameter, top diameter, coordinates, order, etc. The AMAPmod provided 3D graphical reconstructions which were used to check the data. The three-dimensional digitizing proved to be the first rapid measurement method providing a precise and complete numerical 3D representation of woody root systems. Parameters of the structural root system architecture of pine and oak saplings have been obtained and numerous functions required to describe a plant root system can be estimated from the data.

Danjon, F., T. Fourcaud and D. Bert. 2005. Root architecture and wind-firmness of mature *Pinus pinaster*. *New Phytologist*. 168:387-400.

(Note: This paper offers a good description of how to quantitatively characterize tree coarse root architectures).

This study characterized the coarse root architecture of both damaged and undamaged maritime pine (*P. pinaster)* root architecture and tested the hypothesis that the undamaged trees resisted uprooting both because of preferential root volume allocation to key compartments for stability and because of prevailing wind-oriented root volume reinforcement in these compartments. Undamaged and uprooted trees were sampled in a stand damaged by a storm. Root architecture was measured by three-dimensional (3-D) digitizing. The distribution of root volume by root type in wind-oriented sectors was analyzed. General stem and root system characteristics, root volume distribution by compartments, root volume distribution by circular sector, and multivariable comparisons of trees were described. The authors concluded that their findings confirm a previous concern of a possible biomechanical adaptation of the root system to the prevailing wind in trees resistant to wind. In maritime pine (*P. pinaster)*, a mature stem that is resistant to storms is mainly anchored on the ground by a large, leeward, reinforced root cage forming a broad and rigid soil plate that is firmly anchored by windward reinforced shallow roots. Uprooted trees showed a lower cage volume, a larger proportion of oblique and intermediate depth horizontal roots and less wind-oriented root reinforcement.

Davidson, G. R., B. C. Laine, S. J. Galicki and S. T. Threlkeld. 2006. Root-zone hydrology: Why bald cypress in flooded wetlands grow more when it rains. *Tree-Ring Res* 62:3-12.

Abstract: Baldcypress (*Taxodium distichum*) is known to respond to increases in precipitation with increased radial growth even when rooted in continuously saturated sediments where water is not a growth-limiting factor. Measurements of delta O_{18}, ClH_3 and hydraulic head in surface water and shallow groundwater in an oxbow lake-wetland in northern Mississippi show that rapid downward flow of surface water into the root zone is initiated only after precipitation-induced increases in surface water depth exceed a threshold value. Rapid flow of surface water through the root zone has the potential to introduce oxygen to sediments that would otherwise be anoxic, facilitating nutrient uptake and growth. Climatic reconstruction using tree rings from bald cypress in this environment appears possible because increases in precipitation generally correlate well with increases in water level, which in turn enhances the delivery of oxygenated water to the roots.

Dawson, T.E., and J.S. Pate. 1996. Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia*. 107:13-20.

In western Australia, Tasmania blue gum or blue gum eucalyptus (*E.* Globulus), red river gum (*E. camaldulensis)* and bull banksia (*Banksia grandis)* indicate that root systems were dimorphic. Actual root architecture varied, but each had systems of shallow lateral roots (upper 15.6 inches (40 cm)) that supplied water uptake during wet periods. Their deep tap roots or sinker roots supplied water during the dry periods. Tap roots and deep sinker roots could be found to 22.9 ft (7m) deep

Day, M. W. 1944. The root system of aspen. *American Midland Naturalist.* 32(2):502-509.

Complete excavation of aspen roots occurred. An eight year old tree had a lateral root maximum length of 30 ft (9.1 m). An 18-year-old tree had a maximum lateral root length of 47 ft (14.3 m) and a maximum vertical root 7.5 ft (3.4 m) deep. The majority of the lateral root system is contained within 1 foot (.3 m) of the soil surface.

Di Iorio, A., B. Lasserre, G. S. Scippa, and D. Chiatante. 2005. Root system architecture of *Quercus pubescens* trees growing on different sloping conditions. *Annals of Botany.* 95: 351-361.

(Note: A good paper regarding methods of quantification of root architecture). The aim of this work was to assess the influence of slope on the architecture of woody root systems of downy or pubescent oak (*Quercus pubescens*). Biomass allocation within the structural root system and symmetry in the first- and second-order laterals were examined. The root volume was used instead of the root diameter or cross-sectional area (CSA) for the assessment of the center of mass. Analyses based on cross-sectional area and root volume were compared; the latter parameter was more suitable than a single cross-section to analyze morphological information (bending, strong taper) relative to each single root axis. A low-magnetic-field digitizing device was used to measure the X, Y, Z position coordinates of roots together with the diameter and the branching structure. Co-ordinates were determined every 3.9 to 7.8 inches (10–20 cm) when roots were straight and every 0.78 inches (2 cm) when roots were highly bent or tapered. All roots with a proximal diameter larger than 0.07 inches (2 mm) were measured. The symmetry of root systems was evaluated in terms of center of mass of all the first-order lateral roots. Analysis of branching was conducted using the same criteria of the center of volume, with the number of branching points of all the individual roots up to a defined radial distance in place of the root volume. Soil resistance to penetration was measured at field capacity with a Pen-ST-308 penetrometer. Results showed that the slope affected the root volume for each branching order, and the basal cross-sectional area (CSA), number and length of the first-order roots. Sloping trees showed a clustering tendency of the first- and second-order lateral roots in the up-slope direction. In a steep-slope condition, the tap root tapering was positively correlated with the asymmetry magnitude of first-order roots. The author concluded that on a slope, on clayey soils, root asymmetry appears to be a consequence of several environmental factors such as inclination, shallow-slides and soil compactness. In addition, this adaptive growth seems to counteract the turning moment induced by the self-loading forces acting in slope conditions, and as a consequence improves the tree stability.

Drexhage, M., M. Chauviere, F. Colin and C. N. N. Nielsen. 1999. Development of structural root architecture and allometry of *Quercus petraea*. *Can J Forest Res.* 29:600-608.
The mature root systems of sessile oak and pedunculate oak are characterized as a "heart-sinker root systems" consisting of horizontal roots and a tap root from which oblique and vertical roots develop. This mixed form makes the tree less vulnerable to windthrow than the simple heart or sinker root system. In this paper, root growth direction, radial distribution of roots, and biomass partitioning within the root system of 28-year-old sessile oaks were examined using a ROOTARCH method. The ROOTARCH is used to analyze the spatial configuration of structural roots and root/shoot relations, as well as to describe the root system relative to a reference system made of three cylinders. Mean percentages of total cross-sectional area of root types with increasing distance from the stem-root base for oak trees from neighboring 20- and 28-year-old natural regeneration plots were listed. Results showed that with increasing stem diameter, the root biomass was allocated predominantly to and evenly distributed area within the surface root system, effectively increasing tree stability. Root system architecture is inherently determined and DBH or proximal root diameter measurements are sufficient to predict root biomass of young sessile oak when sail properties are nonrestrictive.

Drexchange M., and F. Gruber. 1998. Architecture of skeletal root system of 40-year-old *Picea abies* on strongly acidified soils in the Harz Mountains (Germany). *Canadian Journal of Forest Resources*. 28:13-22.
The object of this study was to determine if the above-ground symptoms of forest decline are reflected in below-ground attributes of the root systems of 15 forty-year-old Norway spruce (*Picea abies)* trees. The mature root system of this species is characterized as a sinker root system consisting of horizontally spreading roots from which vertical or sinker roots develop. The maximum depth of root penetration occurred beneath or adjacent to the stem by either tap roots or vertical sinker roots. The mean biomass was significantly lower on the south slope than on the north slope and on plateaus. The number of root branches was positively related to the length of root; the mean number of branches-per-root-system was significantly lower on the south slope than on the north slope and plateau. Similar to other conifers, more than 90% of vertical roots (sinkers) of Norway spruce occurred near the stem-root base with only a small number of sinkers with a small diameter reaching the maximum rooting depth of 3.28 ft (1 m). These results suggest that the influence of microsite conditions is small compared with inherent regular development processes, which ensure an evenly spreading root system.

Dupuy, L., T. Fourcaud and A. Stokes. 2005a. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil* 278:119-134.

A computer program, SIMUL3R, was developed to determine the anchorage efficiency of four typical root system architectures in theoretical soils representing a wide range of mechanical characteristics. The four root system types were heart, tap-, herringbone- and plate-like root systems. The program which generates root architecture was based on three main modules: INITIALISATION, EXTENSION, and VOLUME. Various types of root structures can be constructed using the SIMUL3R program, by varying the morphological functions f_ growthI(X), f_ram(X), f_ratio(X) and f_taper(X). The overturning resistance of the four schematic root patterns was determined in four different idealistic soil types. Results showed that soil internal friction modified the position of the rotation axis during tilting of the root/soil plate. Rooting depth was a determinant parameter in sandy-like soils. Overturning resistance was greatest in heart- and tap-root systems whatever the soil type. However, the heart root system was more resistant on clay-like soil whereas the tap root system was more resistant on sandy-like soil. Herringbone and plate root systems were twice as less resistant on clay soils and 1.5 times less resistant on sandy soils when compared to heart and tap-like structures.

Dupuy, L., T. Fourcaud, A. Stokes and F. Danjon. 2005b. A density-based approach for the modeling of root architecture: application to Maritime pine (*Pinus pinaster* Ait.) root systems. *Journal of Theoretical Biology*. 236(3):323-334.

Authors developed a new modeling approach using general density functions based on the mathematical representation of the distribution of root properties such as number, angle or diameter. The model was built in 2D and tested on 50 year old Maritime pine (*Pinus pinaster*) to determine the similarity to simulated root models. The simulated and real root systems had similar root distributions in terms of radial distance, depth, branching angle and branching order. These results indicate that general density functions are not only a powerful basis for constructing models of architecture, but can also be used to represent such structures when considering root/soil interaction. These models are particularly useful in that they provide a local morphological characterization which is aggregated in a given unit of soil volume.

Eis S. 1987. Root systems of older immature hemlock, cedar, and Douglas-fir. *Canadian Journal of Forest Resources*. 17:1348-1354.

In this study, the root systems of eight western hemlock, eight western cedar and six Douglas-fir trees, averaging about 50 years old and 10.3 inches (26.3 cm) DBH, were hydraulically excavated. The sizes and shapes of the root systems are described. Fresh and dry weights of the root systems were similar for all three species. It was reported that soils had a large influence on root spread (greater than tree species) and the greatest spread was attained in sand. Initial root growth appeared to be genetically predisposed, but soon modified by soil and plant factors. In Douglas-fir, the roots extend well beyond the perimeter of the crown

and asymmetrically on steeply sloping ground. Roots of all three species tended to follow decaying roots of previous forest or buried rotten wood. All structural roots are of large diameter and taper rapidly to about 1.1 inches (3 cm) at the distance of about 6.5 ft (2 m) from the stump. Roots penetrating to the bedrock bend along it without distortion. The shape of the root systems of hemlock and cedar allow it to survive in wet habitats and to develop a shallow, plate like root system. Douglas-fir suffers irreversible damage after 3-4 weeks of flooding.

Evans G.N. 1970. A technique of simulation of radial root growth in soil and some experimental results. *Soil Science.* 109(6). 376-387.

This paper reports experiments in which a radially growing root was simulated by a cylindrical rubber tube forced to expand in a pack of soil by application of internal pressure. The object was to test the technique, which was new, and to observe the internal pressure/soil deformation relationship and to see how the soil deformation depended on the soil bulk density. The artificial roots (thin rubber tubes) were inserted into a cell filled with Merrimac sandy loam from Windsor, Connecticut (USA) and capped. Water was forced into the tube simulating radial growth. Pressure was slowly applied over a period of 2-4 days. At the end of the experiment, the tubes were removed and plaster casts were taken of the cavity left behind. Soil deformability was constant. Drier water content soil was more easily deformed than wetter soil. Deformation was dependent on bulk density.

Falkiner, R. A., E. K. S. Nambiar, P. J. Polglase, S. Theiveyanathan and L. G. Stewart. 2006. Root distribution of *Eucalyptus grandis* and *Corymbia maculata* in degraded saline soils of south-eastern Australia. *Agroforestry Systems* 67:279-291.

(Note: A good paper on how to determine spatial distribution of root systems). This study compared three different methods for determining root distribution in soil profiles, and investigated the effect of ripping, tree position and soil properties, especially the presence of shallow watertables and site preparation practice, on the vertical and horizontal distributions of Rose gum, (*Eucalyptus grandis)* and spotted gum (*Corymbia maculate)*. The authors sampled roots by using: (i) number of roots intercepting the vertical plane of the soil profile, (ii) root length density (L_v) in soil cores taken at different depths but in the horizontal plane of the profile, and (iii) root length density (L_v) in soil cores in the vertical plane at different radial positions from trees. Data was statistically analyzed to estimate within plot variation for a range of measured parameters. Results showed that there was no clear difference in radial distribution between the three sites although overall rooting density was influenced by species and site. Root distributions in the surface soil were similar at all sites but differences in root growth in the capillary zones paralleled differences in groundwater uptake by trees. Roots were sampled to a depth of 2.8 meters. Root length density for all root diameters combined declined substantially with depth down to 0.3 m and then remained nearly constant to a depth of 1.6 m to 2.0 m. Depending on species, root length density then increased to levels similar to that in the 0 to 0.5 m depths.

This increase in root length density at greater depths occurred just above the water table. The increase occurred for two of the study species but was more pronounced in one than the other. Horizontal cores did not produce results similar to other methods.

Fleischer, F., S. Eckel, I. Schmid and M. Kazda. 2006. Point process modeling of root distribution in pure stands of *Fagus sylvatica* and *Picea abies*. *Canadian Journal of Forest Res*ources. 36:227-237.
Planar point process models were applied to investigate the spatial (two-dimensional) distribution of coarse roots greater than 0.7 inch (2 mm) diameter in pure and mixed stands of Norway spruce (*Picea abies* (L.) Karst.) and European beech *(Fagus sylvatica* L.). In every stand, ten 6.5 ft x 3.2 ft (2 m x 1 m) soil pits were excavated, leading to 20 vertical profile walls of European beech and 16 vertical profile walls of Norway spruce that were analyzed. In most cases 13-19 trees were within a radius of 32.8 ft (10 m) around the pit center. The minimum distance from the pit center to the nearest tree ranged from 1.6 to 9.1 ft (0.5 to 2.8 m). All living small roots of size 0.07 to 0.19 inches (2–5 mm) were marked with pins and digitally photographed. These pictures were evaluated, and a coordinate plane was drawn over each profile wall **W**, so that every root corresponded to a point Xn in the plane. Data analysis and simulation were done using the GeoStoch library system. Results indicated that Norway spruce had stronger clustering in smaller cluster regions, while roots of European beech formed weaker clusters in larger cluster regions. Furthermore, beech root clusters seemed to avoid overlapping. European beech has a more sophisticated rooting system than Norway spruce.

Gifford, G. F. 1966. Aspen root studies on three sites in northern Utah. *American Midland Naturalist*. 75(1):132-141.
ABSTRACT: Aspen *(Populus tremuloides* Michx.) root distribution was studied on the Davis County Experimental Watershed (DCEW) near Farmington, Utah, At the DCEW two "clone groups" consisting of 9 and 15 trees, respectively, in sandy loam soil and one of five trees in clay were identified by the use of eosin (a bluish dye) as a tracer, and were then excavated to determine rooting habits. A single tree was excavated in Cowley Canyon. Nine of the 29 trees sampled had no vertical adventitious roots and 12 had no lateral root development. Seven trees had no root development whatsoever other than the parent root from which they originated; six others had only a single adventitious lateral or vertical root. Root development was similar in all soils except that small roots were nearly absent in the clay. Root depth at the DCEW exceeded 114 inches (290 cm) in sandy loam and 50 inches (127 cm) in the clay. At Cowley Canyon rooting depth in loam with a dense clay B horizon exceeded 60 inches (152 cm) for a tree of age 52 years. The majority of roots in all soils were concentrated in the top 4 ft of soil. The total length of the parent root between terminal ramets was 113.2 and 56.8 ft (35 and 17 m), respectively, in the two clones in sandy loam and 20.5 ft (6.2 m) in the clone growing in clay on the DCEW. Parent root depth varied from 0.2 to 3.3 ft

(.06 – 1m). Lateral roots (one in Cowley Canyon and four from the two clones in sandy loam on DCEW) extended 26, 26.5, 10, 8 and 6 ft, (7.9, 8, 3, 2.4 and 1.8 m) respectively. All ramets appeared to originate at depths ranging from 2 to 12 inches (5 – 30 cm).

Good, R.E. and U.M. Sainju. 1993. Vertical root distribution in relation to soil properties in New Jersey Pineland forests. *Plant and Soil*. 150:87-97.
This study, carried out in the uplands, lowlands and plains of pine-oak and oak-pine forests of the New Jersey Pinelands, was done to investigate the root density and abundance, and their distribution in the soil profiles. Root lengths, density and abundance were collected. Root density and abundance were high in the surface soil and decreased with soil depth in all forest types except in the B horizon where these tended to increase more than the horizons above and below it. A decrease of root density with soil depth for all the forest types suggested that root proliferation may be related to the zones of organic C accumulation, nutrient concentration, and porosity in the soil profile.

Gray, D. 2007. Factors affecting the structural stability and integrity of earthen levees. Vegetation challenge symposium. Sacramento, California August 28, 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm
The presentation focused on damage and failure mechanisms of earthen levees and the role of vegetation is stabilizing such levees. Included was information from earlier studies reported elsewhere in this annotated bibliography. In addition the presentation reviewed an IPET and ILET reports on problems in New Orleans during hurricane Katrina in 2005. The IPET report did not discuss trees and the ILET report mentioned trees only briefly, including information and figures on a tree on levee before and after toppling. No determination of relationship to levee failure was provided. One figure in the presentation documented the potential positive and negative influences of woody vegetation on mass stability of slopes. The slide portraying these influences was not available. Beneficial effect outweighed negative effects two to one. Root reinforcement was mentioned as the most positive influence. Slope failures following vegetation removal was mentioned as a negative effect.

Gray D.H., A.M. MacDonald, T. Thomann, I. Blatz, and F.D. Shields Jr. 1991. The Effects of Vegetation on the Structural integrity of Sandy Levees. REMR Technical Report REMR-EI-5. Department of the Army. 151 p.
This study investigated the relationship between vegetation and the structural integrity of river levees. A specific objective was to determine the distribution of roots within levee embankments, and how these roots alter soil properties of levee embankments and affect their resistance to mass wasting, superficial erosion, piping, etc. The field study was conducted along a 6-mile (9.6 km) stretch of a sandy channel levee along the Sacramento River near Elkton, CA. Trenches were dug and the root systems were examined using a wall-profile method. Primary

tree species included valley oaks (*Quercus lobata*), and shrub willow (*Salix hindusiana*) and elderberry (*Sambucus mexicana*). Lateral roots were restricted to, and modified mainly in, the first two feet of soil depth. Most of the root biomass measure on vertical wall profiles was concentrated in the top 2 ft (.6 m). The authors cautioned that sinker roots and roots vertically oriented may not be characterized and accounted for in vertical wall profiles. Although they thought vertical wall profiles were the best overall technique for assessing root behavior, they suggested more research using excavation of whole root systems was needed to provide appropriate information on vertical roots. Soil voids were nearly completely of ground squirrel and insect origin in the sandy levee soils studied. No voids were clearly attributable to plant roots were observed. Small voids were filled quickly with sediment during floods. Large roots decay slowly and replacement by sediment or new roots is compensatory. The authors found that plant roots reinforced levee soils and significantly increased soil shear strength. Grasses were the best very near the surface, but shrubs (e.g. elderberry) and trees, valley oaks and others, had deeper roots, therefore the increase in shear strength occurs deeper in the soil into the soil, thus protecting soils deeper seated failures. Low growing shrubs and trees offer protection from soil shear while not adding significantly to chance of windthrow and related problems. These findings were restricted to the sandy soils in the region of research. Authors suggest expanding the research to other soils, regions, and species.

Hermann, R.K. 1977. Growth and production of tree roots. *Colorado State University Range Science Department Science Series.* 26:7-28.

The paper begins with a discussion of root systems including primary roots, laterals and adventitious roots. Long root, short root and root hair function is described. Primary root growth depends largely on environmental conditions, mainly temperature and water. As trees age, the most important changes appear to be in the proportion of long and short roots in the root system and in types of roots formed. Four major periods are distinguished in the development of tree roots in Norway: formation of the main root and laterals at ages below 5 years; gradual replacement of the original root system by a system of adventitious roots from about age 5 to 30 years; functioning of the adventitious root system and replacement of dying adventitious roots by new ones during the approximate age span 30 to 90 years; and gradual reduction of capacity for formation of new adventitious roots beginning at about age 90 years. These changes are regulated by environmental influences such as temperature, soil water and aeration, mineral nutrition, and light. The influence of these environmental factors on root characteristics is much stronger than the inherent rooting traits in later stages of development. The density of roots decreased as distance away from the trunk increased. Lopsided crown development resulted in lopsided lateral root development. The annual aboveground and below-ground productivity of various forest types was determined. Spruce trees in Estonia were found to have the highest below-ground growth at 2.7 tons/acre/year (6000 kilograms/hectare/year).

This was followed by poplar in Russia that grew only1.6 tons/acre/year (3600 kg/ha/yr), and radiata pine that grew 1.3 tons/acre/year (3000 kg/ha/yr). The slowest growth was by Scots pine in Germany at only 0.2 tons/acre/year (500 kg/ha/yr).

Hershey, F., D Wallace and John Dwyer. 1994. Forestry Strategies To Protect Floodplain Agricultural Systems. *The Restoration of Aquatic Ecosystems Symposium,* The Association of State Wetland Managers, St. Paul, Minnesota.
No woody vegetation is allowed on levee embankments because:

1. Large trees will windthrow from saturated levees, removing a large soil mass and creating a breach point in the levee.
2. Large tree roots will extend through the levee and cause piping during floods. This is primarily a concern when large, old trees die.
3. Woody vegetation attracts burrowing wild animals to the levee embankment and their activities create breach points in the levee.

Hettiaratchi, D. R. P. 1990. Soil compaction and plant-root growth. *Philosophical Transactions of the Royal Society of London Series B.* 329:343-355.
The paper examines briefly the theoretical aspects of the combined effects of stress and moisture history in modifying both the pore space available for root growth and soil strength that limits the ability of roots to deform the soil. A root extension model was described. Results highlighted the crucial role played by physical factors in the growth processes of roots.

Heyward, F. 1933. The root system of longleaf pine on the deep sands of western Florida. *Journal of Ecology.* 14(2):136-148.
Roots of a large longleaf pine (*Pinus palustris*) were excavated on deep excessively sandy soils in western Florida. This tree was 54 ft (16 m) tall and 17 inches (43 cm) in diameter. Although the tap root divided in two, the longer one was just over 14 ft (4.2 m) deep. Supplementary tap roots developed from laterals near the tree and were generally 4.5 to 5.0 ft (1.4 – 1.5m) in length. A single large lateral root that remained within 10 inches of the soil surface was 71.5 ft (22 m) long before plunging another 3.5 ft (1.1 m) deep and ending. Lateral roots commonly tapered to diameter of 1 inch (2.5 cm) about 12 to 15 ft (3.6 – 4.6 m) from the tree and then were slow to taper after that.

Holtz, W. G. 1983. The influence of vegetation on the swelling and shrinking of clays in the United States of America. *Geotechnique.* 33:159-163.
This paper discusses the effects of tree roots on soil from a different aspect. The desiccation effects of vegetation can cause a significant volume change of soil by shrinking and swelling. In the Colorado-Wyoming area, to control desiccation, all trees should be planted at least 15 ft (4.6 m) from any building, except large water-loving trees which should be kept at least 20 ft (6 m) away. The best approach to remedial measures for desiccation shrinkage damage is the removal of trees.

Hough, W., F.W. Woods and M.L. McCormack. 1965. Root extension of individual tree sin surface soils of a natural longleaf pine-turkey oak stand. *Forest Science.* 11(2):223-242.
Interesting study and method. The authors applied radioactive iodine (I-131) to the soil allowing the iodine to move into the roots, then into the tree stem and vascular system. The surrounding trees are then measured for radioactivity and for their distance from the plot center. An important and interesting find was that elevation, height, DBH, and age were important dependent variables for predicting root extensions for both the pine and oak.

Hruska, J., J. Cermák and S. Sustek. 1999. Mapping tree root systems with ground-penetrating radar. *Tree Physiology.* 19:125-130.
Root systems of forest grown sessile oak (*Quercus petraea)* were scanned to a depth of 6.5 ft (2 m) using ground penetrating radar. A 19.7 x 19.7 ft (6 m by 6 m) scan in 0.82 x 0.82 ft (0.25 X0.25 m) grids of two adjacent trees took 6 hours of scan time and 30 hours of processing. Soils scanned were loamy soils and a 450 MHz signal was used to detect roots down to a 1.1 to 1.5 inch (3 to 4 cm) diameter with a 3.2 to 6.5 foot (1 to 2 m) resolution. Complicating factors were other roots in the same area, stones (not serious for the soil). Maximum coarse roots occurred at 56% of the crown radius to a depth of 6.5 ft (2 m). Authors concluded GPR to be an efficient method for 3-D mapping if forest tree roots in loamy soils.

Jackson, R.B., J. Canadell, J.R. Ehleringer, H.A. Mooney, O.E. Sala and E.D. Schulze. 1996. A global analysis of root distributions for terrestrial biomes. *Oecologia.* 108:389-411.
The authors analyzed rooting patterns for terrestrial biomes and compared the distribution for various plant functional groups using 250 root studies. The eleven biomes were boreal forest, crops, desert, Scler shrub, temperate grassland, temperate coniferous forest, temperate deciduous forest, tropical deciduous forest, tropical evergreen forest, tropical savanna and tundra. For each biome, depth coefficients (β) were determined. β was higher where there was greater proportions of roots with depth. Tundra, boreal forest and temperate grasslands indicated the shallowest profiles (β = 0.913, 0.943, and 0.943, respectively) and 80% 90% of these roots were in the top 11.7 inches (30 cm) of the soil profile. Deserts and temperate coniferous soils indicated the deepest root profiles (β = 0.975, 0.976) with 50% of roots in the top 11.7 inches (30 cm). Highest root biomass was found in the tropical evergreen forest at 11 lbs/yd^2 (5 kg/m^2). Croplands, deserts, tundra and grasslands had the least amount of root biomass at <3.3 lbs/yd^2 (< 1.5 kg/m^2).

Jackson, R.B., L.A. Moore, W.A. Hoffman, W.T. Pockman and C.R. Linder. 1999. Ecosystem rooting depth determined with caves and DNA. *Proceedings of the National Academy of Sciences of the United States of America.* 96:11387-11392.

Below ground community composition and maximum rooting depths of the Edwards Plateau of central Texas were determined using DNA sequence variation to identify roots from 21 caves at between 16.4 and 213.2 ft (5 and 65 m) deep. At least six tree species in the system grew roots deeper than 16.4 ft (5 m). Genera included *Celtis (hackberry), Juniperus (junipers), Quercus (oaks)* and *Ulmus elms*). Only plateau oak (*Quercus fusiformis*) which, along with *Juniperus ashei (ash juniper)* comprised over half of the total species was found below 32.8 ft (10 m). Plateau oak dominated the rooting zones between 26.2 and 72.1 ft (8 and 22 m). Roots were observed above 65.6 ft (20 m) in each of the caves except one. The maximum root depth for the ecosystem was measured at about 85.3 ft (26 m). While root density decreased with increasing depth, there were signs of flexibility with roots growing into areas of higher nutrients or water. The presence of deep-rooted species may enhance ecosystem productivity by leaking water into surface layers where it is available to relatively shallow species such as grasses and forbs.

Jamaludheen, V., B. M. Kumar , P. A.Wahid and N. V. Kamalam. 1997. Root distribution pattern of the wild jack tree (*Artocarpus hirsutus* Lamk) as studied by P-32 soil injection method. *Agroforestry Systems* 35:329-336.
This paper described a method of placing P-32 at various depths and lateral distances from the tree to characterize the distribution of active roots of the wild jack tree (*Artocarpus hirsutus*), in order to provide an insight into the problem of root competition between the tree and other components of mixed species systems. The trees were planted at a distance of 6.5 x 6.5 ft (2 m x 2 m) from each other in 65.6 x 65.6 foot (20 m by 20 m) plots. Nine P-32 treatments formed by combinations of three lateral distances: 29.3, 58.5, and 87.8 inches (75, 150 and 225 cm) from the tree and three soil depths: 11.7, 23.4, and 35.1 inches (30, 60 and 90 cm) were assigned to the 27 experimental units, in a randomized block design. The P-32 activity recovered in the foliage was compared. Results showed that most of the physiologically active roots were concentrated within a radius of 29.3 and 11.7 inches (75 cm and 30 cm) depth, although the tap root might reach even deeper.

Jourdan, C. and H. Rey. 1997. Architecture and development of the oil-palm (*Elaeis guineensis* Jacq.) root system. *Plant and Soil.* 189:33-48.
This study was done to carry out a precise analysis and describe the growth dynamics and architecture of the oil-palm root system. Four growth phases were studied; juvenile (0-1 year old), field establishment phase (3 years old), adult phase (11 years old), and the limit of economic viability phase (20 years). Plants were partially or totally excavated and two approaches were taken for each different phase; one based on the geometry of the root system and the other based on the different axes making up the system along with their growth and branching process. In the juvenile stage, the radicle and adventitious roots were separated. Lateral roots were contained near the surface and were emitted at an angle of around 90 degrees from the radicle. The first adventitious roots were emitted one month after germination; newer adventitious roots grow larger. Lateral roots

cover the entire length of the primary roots. As the plant goes through the next three phases, more roots and categories of roots are added going from primary vertical and horizontal roots, to secondary horizontal roots, to upward growing secondary vertical roots and downward growing secondary vertical roots, superficial and deep tertiary roots and quaternary roots. The relative position of these types of roots determines a morphological and functional unit of the root system called "root architectural unit".

Kochenderfer, J N. 1973. Root distribution under some forest types native to West Virginia. *Ecology*. 54(2):45-448.
Root profiles were examined from road cuts and strip-mine walls in forest stands from 40 to 60 years of age. Measurement included five soils and three hardwood forest types. Root distribution was similar in all types, but 89 % of roots were in the upper 1.9 ft (0.6 m) of the northern hardwood type, while only 77% of the roots were in this zone in the other two types. The deepest roots were at 13.1 ft (4 m) in the oak-hickory type. Greater numbers of roots were found in blue-grey clay soil layers and these occurred at greater depths. More roots were found in the lighter textured soils. Root channels were present in some soils and often had smaller roots growing within them.

Laclau, J.P., M. Arnaud, J.-P. Bouillet and J. Ranger. 2001. Spatial distribution for *Eucalyptus* roots in a deep sandy soil in the Congo: relationships with the ability of the stand to take up water and nutrients. *Tree Physiology*. 21:129-136.
This study analyzed spatial variability in root distribution of a mature colonial plantation of *Eucalyptus spp.* in the Congo. Three, 7.7 foot (2.35 m) wide soil profiles perpendicular to the tree rows, were studied. Two of these were 6.5 ft (2 m) deep and the third was 16.4 ft (5 m) deep. Soil profiles were divided into 1.95 x 1.95 inch (25 cm^2) cells and roots were counted and categorized by size into three catagories: 0.003 to 0.039 inches (0.1- 1mm), 0.039 to 0.39 inches (1mm - 1cm), and > 0.39 inches (over 1 cm). Soil strength, chemical properties and soil water were also measured. In the top 6.5 ft (2 m) of soil, the fine root density (FRD) was highly heterogeneous in each of the soil profiles. There was a significant decrease in FRD as the soil got deeper. In all soil profiles, the surface soil layer had high FRD. Large lateral roots were found only under the stump. Soil strength was highest at about 3.28 ft (1 m) and decreased sharply at about 4.9 ft (1.5 m). Soil strength decreases as soil water increases. Nutrients such as calcium decrease with increasing soil depth indicating that roots are able to take nutrients quickly from both the forest floor and upper soil layer. Roots preferentially explored the soil under the stump, but root density decreased sharply below 19.5 inches (50 cm) under the stump. The opposite was found in a 37 year-old radiata pine plantation.

Leaf, A.L., R. Leonard and J. Berglund. 1971. Root Distribution of a plantation-grown red pine in an outwash soil. *Ecology*. 52(1):153-158.

This paper deals with tree-root distribution of a dominant, 39 year old red pine growing on a deep, highly stratified outwash Hinckley loamy coarse sand in New York State. The tree was cut at the ground line and separated into components (leaves, branches, bolebark and bolewood). Starting at the stump, all of the soil was removed from soil horizons **A** and **B** and 1ft (0 .31 m) into **C**. All was done by hand to minimize root breakage. Root segments were separated into five diameter size classes: > 0.78 inches, 0.78 to 0.39 inch, 0.39 to 0.19 inches, 0.19 to 0.03 inches, and < 0.03 inches (>2cm, 2-1cm, 1-.5cm, .5-.1cm and <.1cm). Each sample was washed, dried and weighed. Approximately 1/3 of the total root weight was in the A horizon; nearly ½ was in the **B** horizon and nearly 1/5 was in the measured portion of the C horizon. The maximum lateral root radial extension was slightly greater than the live crown length. The maximum rooting depth was ~30% of the maximum lateral root extension. And the maximum lateral root radial extent was in the B horizon 3.9 to 5.9 ft (1.2-1.8 m) out from the root collar.

Le Goff, N. and J. Ottorini. 2001. Root biomass and biomass increment in a beech (*Fagus sylvatica* L.) stand in North-East France. *Annales of Forestry Science.* 58(2001):1–13.
Study attempted to quantify root biomass of European beech or copper beech (*Fagus sylvatica* L.) trees. A sample of 16 trees showed that root biomass was highly correlated to tree diameter. The proportion of coarse root biomass increased with increasing tree diameter. Regression equations accounted for 99% of the variation in coarse and small root biomass, and 94% of the fine root biomass. Coarse root biomass represented an average of 86 % of the total root system.

Leuschner, C., D. Hertel, H. Coners and V. Buttner. 2001. Root competition between beech and oak: a hypothesis. *Oecologia.* 126:276-284.
This study investigates the below ground competition between fine roots of adult European beech and sessile oak trees in a mixed temperate beech-oak forest. Field experiments showed that beech grew more rapidly than oaks when both were grown together in a controlled environment. When stem densities and leaf areas were similar, beech had significantly more, fine root biomass and a much greater root: shoot ratio (3.9 compared to 1.7 for oak). Oaks on the other hand, outnumbered beeches in coarse roots. The fine root systems of the two species overlap but beech root biomass increased with increasing distance from the stem, whereas oak root mass was not dependent on stem distance. Beech root mass was correlated with the thickness of the organic topsoil horizons while oak was not. The study concluded that the fine roots of beech trees were more successful in colonizing the upper layers of organic soils than were the oaks.

Lindstrom, A. and G. Rune. 1999. Root deformation in plantations of container-grown Scots pine trees: effects on root growth, tree stability and stem straightness. *Plant and Soil* 217:29-37.

Studies have shown that containers of the Paperpot-type, with smooth inside walls, cause different types of root deformation such as spiraling. The ultimate consequences of root deformation are uprooting due to a weak root anchorage and root breakage. This study investigated young and older plantations of Paperpot-grown plants and naturally regenerated trees with a special emphasis on root development and deformations, stability and stem straightness. Root system deformation was studied in 23 Scots pine stands. Stem base crookedness was estimated by using a digital protractor. In order to measure stability, trees were pulled by a wire attached to a winch. An index of evenness of root distribution, a root area index (RAI), was calculated. The conclusions from this study are that root distribution, tree stability and stem straightness of planted Paperpot-grown trees will improve after a certain time and will eventually approach the state of naturally regenerated trees. As trees grow older, early established crooked stem bases will be compensated by radial growth and the tree will appear straighter.

McElrone, A., W.T. Pockman, J. Martinez-Vilalta and R.B. Jackson. 2004. Variation in xylem structure and function in stems and roots of trees to 20 m (65.5 ft) depth. *New Phytologist.* 163. 507-517.

This study was done to evaluate deep roots regarding their structural and functional characteristics relative to the entire water-flow path of trees. Four tree species were studied, two at Cotterell cave in Austin, TX, ashe juniper (*Juniperus ashei*) and Durand oak (*Quercus sinuata*) and two from Powell's and Leel's caves in Menard, TX, plateau oak (*Quercus fusiformis)* and chittamwood (*Bumelia lanuginosa*). All of these persist on the shallow soils of the Edward's Plateau and are considered slow growing and drought tolerant. For each, stems, deep roots and shallow roots were sampled. Cross sections were examined under microscope and all xylem vessels not filled with tyloses within the sectors between rays were measured. The number of xylem vessels measured per section ranged between 60 and 627. For each vessel diameter class, theoretical hydraulic conductivity was calculated. Conduit diameter was significantly related to the depth in all four species studied. In each case, the vessels were smallest in the stems, intermediate in the shallow roots and largest in the deep roots. Thus the flow capacity increased as depth increased.

McKee, K.L. 2001. Root proliferation in decaying roots and old root channels: a nutrient conservation mechanism in oligotrophic mangrove forests? *Journal of Ecology*. 89:876-887.

The author looked at root proliferation inside decayed/decaying roots and old root channels in peat soils of mangrove forests. The author described soils as soft and without compaction or impenetrable layers well beyond the root zones. This study suggests that the roots were proliferated within the old root channels utilizing decomposed organic matter and nutrients. Artificial channels (PVC pipe) were used to simulate decayed root channels over a two year period. The buried pipe treatments were either empty, filled with sand, or filled with nutrient-rich organic matter. Those with nutrient rich organic matter had six times more roots than pipes containing sand or those that were empty. The results indicated for the mangrove forest studied, that the root responses to old root channels was due more to nutrient availability and not to area of less impedance.

McMinn R.G. 1963. Characteristics of Douglas-fir root systems. *Canadian Journal of Botany*. 4:105-122.
The root systems of 28 Douglas fir (*Pseudotsuga menziesii*) in four stands of varying slopes and soil types, aged 10, 25, 40, and 55 years, were excavated hydraulically to determine the rooting characteristics of trees in different crown classes at various ages. The extent, depth, configuration, rooting density and mycorrhizal component of the root systems were examined. The roots were mapped with a grid system and termed primary, tertiary or quaternary based on their position. The length of dead roots was also noted. The total length of root systems increased with increasing age and crown size. With regard to canopy position, the length, extent and complexity of branching in the root systems of dominants exceeded that of intermediate and suppressed trees of similar age and, in some cases they exceeded those of older trees that were in lower canopy positions. The area of soil encompassed by root systems was more for trees in upper crowns and/or older trees. On level terrain, laterals extended horizontally and more or less symmetrically but on slopes they grew asymmetrically. Laterals on the downslope side descended at a steep angle and did not extend far when they reached deep soil horizons. Laterals on the uphill side maintained a positive angle and often traversed great distances upslope. The roots from immature stands, growing along decaying roots and the channels left when roots of previous stands rotted, may extend much further than roots growing entirely in mineral soil.

Millikin, C. S. and C. S. Bledsoe. 1999. Biomass and distribution of fine and coarse roots from blue oak (*Quercus douglasii*) trees in the northern Sierra Nevada foothills of California. *Plant and Soil* 214:27-38.
Lateral woody roots are usually sampled with quantitative pits. Fine root distributions are usually assessed by soil cores. In order to understand the belowground dynamics of blue oak woodlands, the coarse and fine root biomass of six Blue oak (*Q. douglasii*) (Hook and Arn.) trees in the northern Sierra Nevada foothills were measured using excavation, quantitative pit and core methods. Course root biomass and rooting depth for main root systems were collected. Results showed that lateral root length and number decreased with depth. The primary root generally tapered rapidly below 19.5 inches (50 cm) and either turned horizontally at a root limiting soil layer or terminated with fine roots fanning out from the tip. At surface depths of 0 to 7.8 inches (0-20 cm), small-fine (< 0.019 inch diameter (0.5 mm)) roots accounted for 71%, large-fine (0.019 to 0.7 inches (0.5-2.0 mm)) for 25%, and coarse (> 0.07 inches (> 2 mm)) for 4% of total root biomass collected with cores. Lateral extent of woody roots may exhibit

a high degree of plasticity and depend on environmental conditions. Distance from the tree did not significantly affect fine root biomass within our sampling range. For most trees, biomass within the canopy was similar to biomass at the canopy edge and just outside the canopy. Only the tree with the largest canopy radius exhibited a trend of decreasing fine root biomass with increasing distance (up to 17.7 ft (5.4 m)).

Mou, P., R. J. Mitchell, and R. H. Jones. 1997. Root distribution of two tree species under a heterogeneous nutrient environment. *Journal of Applied Ecology*. 34:645-656.
The goal of this paper is to test the effects of soil nutrient heterogeneity and light on potted sweetgum and loblolly pine seedlings' root development. The spatial development of root systems of both species was strongly influenced by the fertilization arrangements, but they reacted to soil nutrient heterogeneity differently. Fertilization arrangements under full light did not significantly affect most aspects of total plant growth or allometry. Root development in heterogeneous soils differed between light treatments

Nadezhdina, N. and J. Cermak. 2003. Instrumental methods for studies of structure and function of root systems of large trees. *Journal of Experimental Botany*. 54:1511-1521.
The paper reviewed four techniques in studying root architecture and quantifying root physical parameters. The techniques are ground penetrating radar, differential electric conductivity, the excavation technique using a supersonic air stream, and the sap flow technique.

Nicoll, B. C. and D. Ray. 1996. Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiology*. 16:891-898.
Soil-root plate dimensions and structural root architecture were examined on 46-year-old Sitka spruce trees. Results showed that rooting depth was restricted by a water table, and root system morphology had adapted to resist the wind movement associated with shallow rooting. The spread of the root system was negatively related to soil-root plate depth. Root systems had more structural root mass on the leeward side than the windward side of the tree relative to the prevailing wind direction. These forms of adaptive growth in response to wind movement improve the rigidity of the soil-root plate and counteract the increasing vulnerability to windthrow as the tree grows.

Nicoll, B. C., S. Berthier, A. Achim, K. Gouskou, F. Danjon, and L. P. H. van Beek. 2006a. The architecture of *Picea sitchensis* structural root systems on horizontal and sloping terrain. *Trees-Structure and Function*. 20:701-712.
The architectural pattern of plant root systems is a product of the number of roots, their position of origin, initial growth direction, deviation in direction, branching pattern and turnover. In this paper, the coarse root systems of 24 Sitka spruce (*Picea sitchensis*) trees, from a 40-year-old plantation in west Scotland, were

extracted, digitized in three dimensions using a Fastrack 3D digitizer with a LongRanger transmitter. Data were analyzed by AMAPmod software (CIRAD, Montpellier, France). The relationships between course root volume and stem volume, and relationships between allocation of root mass and slope and prevailing wind direction were assessed.

Nicoll, B. C., B. A. Gardiner, B. Rayner and A. J. Peace. 2006b. Anchorage of coniferous trees in relation to species, soil type, and rooting depth. *Canadian Journal Forest Reources.* 36:1871-1883.
Data from tree-pulling experiments conducted in Britain between 1960 and 2000 have now been compiled into a database containing almost 2000 trees from 12 conifer species. In this paper, the authors described a meta-analysis of the tree-pulling data to test the hypothesis that root anchorage of conifers varies between species and soil group, and increases with rooting depth. Anchorage was compared among species, soil groups (freely-draining mineral, gleyed mineral, peaty mineral, and deep peat) and root depth classes (shallow, < 15.6 inches (< 40 cm); medium, 15.6-31.2 inches (40-80 cm]; and deep, > 32 inches (> 80 cm)) using regressions of critical turning moment against stem mass. Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was used as a benchmark because it formed the largest part of the database. Anchorage of Sitka spruce was strongest on, peat and poorest on gleyed mineral soils. Significantly better anchorage than Sitka spruce was found for grand fir. Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) had poorer anchorage than Sitka spruce over a range of soil groups and root depth classes. Norway spruce (*Picea abies* (L.) Karst.) on shallow gleyed mineral soil, and Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) on medium depth mineral soil, also had poorer anchorage.

Nilaweera, N.S. and P. Nutalaya. 1999. Role of tree roots in slope stabilization. *Bulletin Engineering Geological Environment.* 57:337-342.
Authors measured root diameters, lengths, and tensile resistance and determined tensile strength for seven indigenous species in the Khao Luang mountain area of southern Thailand. Tensile strength was defined as tensile resistance divided by the cross-sectional area of unstressed roots. Using regression analysis, the authors determined relationships between root diameter and tensile resistance. Using these relationships, equations were determined to predict root tensile resistance of the tested species according to root diameters. For all seven species, tensile strength decreased with increasing root diameters. Root tensile strengths were determined using an Autograph DCS-5000 Shimadzu testing machine. Samples were taken from unbranched sections of roots from mature trees. Samples were 3.9 to 5.8 inches (100 to 150 mm) long with a maximum diameter of 0.5 inches (15mm). The majority of the samples were small <0.27 inches (< 7mm). The results of these were recorded in the form of elongation versus load curves. Only failure loads and ultimate elongation could be observed for larger samples >0.27 inches (>7 mm). The authors also studied pull-out resistance and root distributions for the same seven species. Horizontal pull-out was not an option due to extensive

root damage. Therefore a vertical pull-out method was used. Trees were saturated and tested after a growth period of one year. Results showed that pull-out resistance is generally controlled by a trees root strength and morphological characteristics. For all seven species tested, root tensile strength decreased with root diameters. Pull-out resistance increased with increased root lengths and root penetration depths. Volumetric root distribution did not necessarily correlate with the pull-out strength of a tree because the same root volumes can be the result of different root lengths and diameters. When examining root volumes, longer roots with smaller diameters had greater root tensile strengths and higher pull-out resistance. Only one of the seven species studied, para rubber (*Hevea brasiliensis*) did not fit the pattern conducive for slope stability.

Oosterban A., and G.J. Nabuurs. 1991. Relationships between oak decline and groundwater class in the Netherlands. *Plant and Soil.* 136:87-93.
This study was conducted to determine the effects of fluctuating groundwater levels to the roots of pedunculate oak (*Quercus robur*) at 11 locations in the Netherlands. The trees were in even-aged stands 40-60 years old. It was found that dead and unhealthy oak trees are most prevalent on soils with strongly fluctuating groundwater in the rooting zone. On these soils, oaks root less deeply and have more dead roots, especially in the deepest part of the root system. The percentage of dead roots was highest in the 0.039 inch to 0.078 inch (1-2 mm) diameter size class and decreased with root diameter. These percentages correlate with groundwater class.

Pagès, L., G. Vercambre, J.-L. Drouet, F. Lecompte, C. Collet, and J. Le Bot. 2004. Root Typ: a generic model to depict and analyze the root system architecture. *Plant and Soil.* 258:103-119.
'Root Typ' model was proposed to dedicate quantitative and global analyses of root system architectures. The model implements several developmental processes including: root emission, axial and radial growth, sequential branching, reiteration, transition, decay and abscission. Its ability to mimic a diversity of root architectures is tested.

Peper, P.J. 1998. *Proceedings of an International Workshop on Tree Root Development in Urban Soils.* The landscape below ground II. International Society of Arboriculture. pp 82-93.
Three year old white mulberry were excavated for root data collection for dry mass, diameters, and root locations to determine if different root barrier products impeded root circling and root biomass reduction. The author was interested in the following types of commercial root barrier products: DeepRoot, Tree Root Planter, and Vespro. The barriers were installed at depths of 11.7 and 23.4 inches (30 and 60 cm). Results indicated that 11.7 inch (30 cm) barriers significantly reduced surface root biomass outside the barriers but did not significantly reduce root diameters. The 23.4 inch (60 cm) depth barriers effectively reduced dry mass

(85 -89%). Root circling was impeded and roots were forced to grow downward, regardless of barrier depth.

Peper, P.J., and S. Mori. 1999. Root barrier and extension casing effects on Chinese hackberry. *Journal of Arboriculture.* 25(1):1-8.
Three year old Chinese hackberry (*Celtis sinensis*) was used to evaluate the effectiveness for three types of root barriers. The authors were interesting in determining whether root barriers with internal vertical ribs could prevent root circling and also could root development be significantly reduced in the top 11.7 inches (30 cm) of the soil. The seedlings measured were planted and grown both with and without the root barriers. The three barriers tested were: 1.) a production container left partially planted (extension casing), 2.) a commercial barrier with vertical ribs spaced 5.8 inches (15 cm) apart and 3.) a commercial barrier with vertical ribs spaced 4.8 inches (12.5 cm) apart. Results concluded that circling restricted barriers with vertical ribs were used. Root biomass was reduced by 50% for root barriers with the extension casing. The two commercial barriers measured had mean root diameters and biomasses that were similar. Any roots that circumvented the barrier walls grew upward to levels that were similar to the control trees.

Peterson, C. 2007. Tree, site, and soil influences on tree uprooting in forests. Vegetation challenge symposium. Sacramento, California August 28, 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm
This presentation dealt primarily with tree falls and those factors influencing the uprooting or breakage of trees. The presentation reviewed several factors contributing to wind damage and windthrow including hurricanes, tornados, coastal winds, tree and stand characteristics; and site characteristics. The presenter mentioned the paucity of information related to the effects of wind on trees occupying levees or the species in review at the symposium. The presentation contained information on drag forces of crowns relative to wind and the differences produced by species, tree size, and wind speed. Crown deformation effects during storms was also mentioned. The biomechanics of breakage versus bending and windthrow were also discussed. Site characteristics and topography also affect forces on trees. Soil saturation and hardpans within soils limit the extent of rooting and therefore influence windthrow risk on some sites.

Pittenger, D.R. and D.R. Hodel. 1999. Effects of root barriers on tree and root growth. *Proceedings on the UCR Turfgrass and Landscape Management Research Conference and Field Day.* p 1-2.
This study examined the influence of different types of physical surround-type root barriers on surface root development and tree growth. The six year old study used two species sweetgum (*Liquidambar styraciflua)* and Indian laurel (*Ficus nitida)* to determine the effectiveness of root barriers in limiting the growth of surface roots outside of the barrier area. The treatments ranged from a "DeepRoot" barrier (24 inches deep (61 cm)) to sleeves, or five-gallon buckets

with the bottoms removed. The results indicated that with each treatment (barrier) the roots do return to the surface once they get outside of the barrier. However, the study did indicate that surround-type barriers can reduce the number of surface roots the form immediately outside the barrier. Several of the barriers are effective in eliminating large roots at least a few feet from the trunk but only for a limited time. The roots that do return to the surface seemed to be relatively small and would probably not create a large amount of damage to hardscapes

Putz, F.E., P. D. Coley, K. Lu, A. Montalvo, and A. Aiello. 1983. Snapping and uprooting of trees: structural determinants and ecological consequences. *Canadian Journal of Forest Research* 13:1011-1020.
The influence of mechanical and architectural properties of trees on growth rates, mortality rates, and relative probabilities of snapping and uprooting were examined on Barro Colorado Island, Republic of Panama. Of 310 fallen trees, 70% snapped, 25% uprooted, and 5% broke off at ground level. Stepwise discriminant analysis between snapped and uprooted trees indicated that the variable measured, wood properties were the most important factors determining the type of death in trees. Uprooted trees tended to be larger, shorter for a given stem diameter, and to have denser, stiffer, and stronger wood than snapped trees. There were no significant differences between trees that snapped and trees that uprooted in the extent of buttress development or in the slope of the ground upon which they grew. Trees with low density wood grew fast in stem diameter that those with high density wood but also suffered higher mortality rates. After damage, many of the snapped trees sprouted; small trees sprouted more frequently than large trees. Sprouting is proposed as a means by which weak-wooded fast-growing trees partially compensate for being prone to snapping.

Randrup, T.B., E.G. McPherson and L.R. Costello. 2001. A review of tree root conflicts with sidewalks, curbs, and roads. *Urban Ecosystems.* 5:209-225.
This article is not so much of a study as it is a review. The authors review factors that cause higher conflict for tree roots and curbs, roads, sidewalks, etc. and they also provide an overview of cost inferred to cities by root/structure conflicts. The authors also address the new areas for research. The review suggest that the potential for conflict is higher when one or more of the following is present: 1.) tree species that are large at maturity, 2.) fast growing trees, 3.) shallow top soil, 4.) shallow foundation under the sidewalk, 5.) shallow irrigation, 6.) trees planted in restricted soil volume, 7.) distance between the tree and sidewalk of less than 6.5 to 9.8 ft (2 to 3 m), 8.) trees greater than 15 to 20 years old. The article also discussed the different types of barriers and their possible effects on root growth.

REMR. Vegetation and structural integrity of Levees: Results of Field Investigations. *REMR Technical Note EI-M-1.3.* Suppl 1.3. 1-4.
This was a study of the amount, distribution and effects of root materials of various type vegetation, growing on levees on the Sacramento River. Six locations were

studied, each with different vegetation (herbaceous vegetation and shrubs, living valley oak, dead valley oak, willow, elderberry, and black locust). L-shaped trenches 3.28 ft (1 m) deep were dug in the sandy levee within the crown of the dominant species at each site. Root location and diameter were mapped and used to calculate a root area ratio (RAR). Most of the roots of the shrub site were within the top 4 inches. Roots of the living valley oaks and the willows dominated the area between 4 and 12 inches. Elderberry had the highest RAR at 28 inches but overall, the valley oaks, both dead and living had consistently high RAR. The dead valley oak had a large tap root at 4.6 ft (1.4 m) and lateral roots of less than 0.32 ft (0.1 m) even after 20 years of decay. Areas where roots had decayed were filled in with sand.

Schaetzl, R.J., S.F. Burns, T.W. Small, and D.L. Johnson. 1990. Tree uprooting: review of types and patterns of soil disturbance. *Physical Geography*. 11 (3):277-291.
This paper summarizes part of the extensive literature concerning soil disturbance by tree uprooting. The authors found that the initial size of the pit and root plate is a function of tree size and rooting habit, the eventual dimensions of the pit/mound pair are conditioned by the quantity of sediment that returns to the pit via slump and wash process. Uprooting disrupts soil horizonation and retards soil development. There was a positive correlation between tree diameter at DBH and area of soil disturbed. Rooting depths increased as tree size increased up to 40 cm DBH, after which root systems did not appear to expand. On steep slopes, uprooted trees generally fall downslope, producing a net downslope transport of sediment. Uprooting also plays an important role in sediment transfer via input to landslides. Tree throw pits collect water and thus cause a reduction in soil shear strength, a natural triggering mechanism for debris avalanches and debris flows.

Schenk, H.J., and R.B. Jackson. 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. *Journal of Ecology*. 90:480-494.
This study was performed to predict root system sizes and shapes for different plant growth forms using data on above-ground plant sizes, climates and soil textures. A review of more than 1,300 plants and data was collected for deserts, scrublands, grasslands and savannas. Maximum rooting depths, maximum lateral root spreads and their ratios were measured. It was found that the root system sizes differed among the growth forms and increased with above ground size. Trees were largest followed by shrubs, semi-shrubs, grasses and perennial forbs, and finally annuals. Root depth increased with increased mean annual precipitation in all cases except trees and shrubs. In every type except trees, root systems tended to be shallower and wider in dry and hot climates and deeper and narrower in cold and wet climates. In relation to the above-ground plant sizes, root system sizes decreased with increasing potential evapotranspiration for all growth forms, but decreased with increasing mean annual precipitation only for

herbaceous plants. Thus, relative rooting depths tended to increase with aridity, although absolute rooting depths decreased with aridity.

Schenk, H.J. and R.B. Jackson. 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma*. 126(2005):129–140.
Review article. The study indicates that less than 10% of articles on roots provide measurements of maximum root depths. The authors used the literature and predictions from the literature (Global root databases) to map the distribution of deep roots (deep rooted plants were plants with greater than 5% of the roots deeper than 6.5 ft (2m)). Trees were then associated with the climatic patterns and soil textures from which they came. Cumulative vertical root profiles were interpolated predict the depths containing 95% (D95) of all roots in a profile. Prediction of the likelihood of plants producing deep roots was greatest for those growing in areas with pronounced wet and dry season differences, those with fine soil textures or coarse soil textures (but not medium texture).

Schmid, I. and M. Kazda. 2001. Vertical distribution and radial growth of coarse roots in pure and mixed stands of *Fagus sylvatica* and *Picea abies*. *Canadian Journal of Forest Resources*. 31:539-548.
Radial growth of European beech and of Norway spruce root was assessed for roots greater than 0.2 inches (5 mm) diameter by growth ring analysis, in order to identify links between root distribution and radial root growth parameters. The trench profile wall technique was used in this study. On each plot, 10 soil pits with a size of 6.5 x 3.2 ft (2 m × 1 m) were excavated to 3.2 foot (1 m) depth. On each plot, 10 soil pits with a size of 6.5 x 3.2 ft (2 m × 1 m) were excavated to 3.2 foot (1 m) depth. In most cases, 13–19 trees were within a radius of 32.8 ft (10 m) around the pit center. Root mapping was done on each profile wall in each soil pit. On each wall, all coarse roots (diameter >0.7 in) were identified according to species and divided into living or dead. In the mixed stand, the roots from different species were separated by optical criteria. Results showed that radial root growth of beech exceeded that of spruce significantly in both pure and mixed stands. Radial growth rate of beech roots further increased when mixed with spruce. Neither root diameter nor root growth of any species was correlated with soil depth. Roots of both species reached the maximum excavation depth of 3.2 ft (1 m) in their monospecific stands. However, the root system of spruce was shallower in the mixture with beech, where large roots (diameter > 0.78 in) were limited to the upper 3.9 inches (10 cm).

Shields, F.D. 2007. Role of vegetation in levee slope stability and revetment durability. Vegetation challenge symposium. Sacramento, California. August 28, 2007. http://www.safca.org/LeveeVeg-SpeakerPanel.htm
Presentation included report on studies done in the 1980s and early 90s on six sites along the Sacramento River. Soils, vegetation and root size and distribution were outlined relative to stability of levees. Data were used to conduct a slope stability evaluation. Root area ratios (RAR) were used to discuss root distributions

within the soil profiles and make comparisons among different types of vegetation assuming similar relationships between RAR and soil cohesion that Gray found in laboratory tests. Using this relationship both an infinite slope stability analysis and a circular arc analysis of slope failure were performed. Vegetation increased levee stability. Prediction of levee failure occurred when vegetation was absent from the levees. Deeper rooted plants, trees and shrubs, produced better stability under the circular arc conditions. Roots increased soil cohesion 50%, but had major impact on the safety factor. Aerial photographs before and after a 1986 flood were used to confirm predictions. One acknowledged limitation is that they did not consider windthrow or seepage in their models of levee slope failure. Comparing vegetated and unvegetated revetment areas they found that revetments with vegetation had less damage than those without vegetation.

Shields, F. D. and D. H. Gray. 1992. Effects of Woody Vegetation on Sandy Levee Integrity. *Water Resources Bulletin*. 28:917-931.
This is one of the papers closely related to the research project.
The influence of woody vegetation on the reliability of a sandy levee along the Sacramento River 12.4 miles (20 km) northwest of Sacramento, California was investigated. Dominant woody species on both levee slopes included valley oaks (*Quercus lobata*) and cottonwood (*Populus fremontii*). Root architecture and distribution were determined using the profile-wall method in which root cross sections were exposed in the vertical wall of an excavated trench. Transects running both parallel and perpendicular to the crest of the levee were excavated at six sites. Roots reinforced the levee soil and increased shear resistance in a measurable manner. The findings suggest that allowing woody shrubs and small trees on levees would provide environmental benefits and would enhance structural integrity without the hazards associated with large trees such as wind-throwing.

Smiley, E.T. 2005. Root growth near vertical root barriers. *Journal of Arboriculture.* (Research Note) 31(3):150-152.
Study examined growth patterns for a variety of vertical root barriers for the species Willow oak (*Quercus phellos*). The study site was on a clay loam soil in Charlotte, North Carolina. Five treatments were used and consisted of the various types of barriers; 1.) DeepRoot Tree Root Barrier with 0.08 inch thick copolymer polypropylene panels, 2.) DeepRoot Tree Root Barrier with Spin Out (a copper resin coating), 3.) Typar geotextile 3801, a heavyweight, nonwoven polypropylene geotextile fabric, 4.) Biobarrier, a medium weight, nonwoven polypropylene geotextile fabric with attached nodules containing a herbicide, 5.) Tx-R Barrier, a heavyweight, needle punched, nonwoven polypropolene, polyester coated with Spin-out (copper resin coating), and 6.) control treatment was no barrier. Root sizes were less than 0.5 inches (1.28 cm) in diameter. No roots penetrated any of the barriers although some roots grew beneath the barrier and then grew upwards. The study looked at roots within the barrier and six inches outside the barrier. There were significantly more roots in the measured

plane outside the barrier for the control treatment than all other barrier treatments. Roots were counted at three depths in this plane; surface and a depth of 12 inches (30 cm), 12 – 18 inches, (30 – 46 cm) and below 18 inches (46 cm). There were no differences in barrier treatments within the barrier zone. There were more roots in the control area for this zone as well. There were no differences in parallel spread for any of the treatments although all five of the root barriers seemed to have affected the growth patterns. It was determined that root growth where a barrier was installed was greatly reduced when compared to the control treatment. The chemically treated barriers were best at suppressing root growth.

Smiley, E.T., A. Key and C. Greco. 2000. Root barriers and windthrow potential. *Journal of Arboriculture.* 26: 4. 213-217.
This study determined that ribbed barriers increased the stability under severe lateral stress. The authors tested six green ash (*Fraxinus pennsylvanica*) without barriers and six were planted in surround-type root barriers. Three of each group were pulled under dry soil conditions (14% water) and three of each group were pulled under saturated conditions (33% water). Wind resistance and the force required to pull each tree was measured. Trees grown within the root barriers were slightly harder to pull than those without. Deep roots were thought to be the reason for the barrier trees having increased strength. There were no trunk failures as a result of the stable root systems. The control trees broke at either the stem or at the root collar. There were no differences in the patterns of failure for the saturated soil conditions (33%). Roots pulled out of the ground had breakage for root sizes 0.25 to 0.5 inches (.6 – 1.27 cm) in diameter. Under the wetter soil regime, trees with root barriers withstood higher forces than did the controlled trees possibly due to the deep rooting of the barrier trees. Roots of the trees with barriers typically had root depths of 12 – 16 inches (30 – 41cm) deeper than the control trees.

Smith J.H.G. 1964. Root spread can be estimated from crown width of Douglas fir, lodgepole pine, and other British Columbia tree species. *Forestry Chronicle.* 40:456-473.
Detailed studies of root systems were made by excavation of roots of trees blown down in the U.B.C. Campus Forest. Roots of 89 Douglas fir, 81 western hemlock, 61 western red cedar, and 33 red alder trees were mapped and analyzed in relation to 18 trees and stand variables including DBH, height, crown class, butt diameter, average branch length, and average root diameter and length. The soil texture was either gravelly or sandy and no heavy textured soils were studied. The average branch length proved to be a useful basis for estimation of root spread as the root spread of all species was slightly less than the branch length. Use of DBH by itself to estimate root spread was slightly better than use of crown width to estimate root spread. The number of main lateral roots increased directly with DBH. The variation in percentage of the root zone occupied by roots was high between species. The greatest total volume occupied by roots occurred in dry moisture regimes. The greatest root spread in relation to volume of soil occupied

by roots occurred in wet to very wet soil moisture regimes where rooting depth is limited.

Stathers, R.J., T.P. Rollerson and S.J. Mitchell. 1994. Windthrow Handbook for British Columbia Forests. *Ministry of Forests Research Program Working Paper 9401.* p 1-31.

This handbook was written to give users an introduction to windthrow and to suggest possible options of assessing windthrow hazards and managing windthrow to minimize its impact. There are six sections. Section one is an introduction to windthrow and its potential for damage in British Columbia. Section two provides background information and presents a categorization of windthrow; catastrophic windthrow is infrequent, occurring only with extreme winds and resulting in extensive damage to large areas and endemic windthrow is more regular and smaller scale. This section also describes various types of wind damage such as stem break, root break and tree throw. Section three examines the mechanics of windthrow based on numerous factors such as wind speed, crown size and density, tree height, wood strength, root-soil weight, root strength, and the shape of the tree. Section four breaks down the factors into: 1.) individual tree characteristics, 2.) stand level characteristics, 3.) soil characteristics, 4.) topographic characteristics and 5.) meteorological conditions. Section five offers an evaluation of windthrow hazard describing high risk, low risk and moderate risk stands. Section six explains some management strategies to be used in clearcutting, edge stabilization, partial cutting and regeneration.

Stokes, A. 1999. Strain distribution during anchorage failure of *Pinus pinaster* Ait. at different ages and tree growth response to wind-induced root movement. *Plant and Soil.* 217:17-27.

Tests were carried out on 5, 13, and 17-year-old tap-rooted Maritime pine (*Pinus pinaster*) in order to determine how the mode of anchorage failure changes throughout the life of a tree. The mode of failure changed with tree size and anchorage strength increased proportionally with the third power of the trunk diameter; therefore another reason why failure differs with tree age must exist. In order to determine if different types of wood were being laid down in the lateral roots in response to wind loading, maturation strains (indicating the existence of mechanical stress in developing wood cells) were measured at different points along the roots. A high correlation was found between maturation strain and strain measured during winching in roots that lay in the wind direction only. Therefore, trees appear to be able to respond to external loading stress, even at a local level within a root. Resistance to stem breakage increases as a function of DBH^3 whereas resistance to uprooting has been found to be a function of height x DBH^2. This suggests that anchorage systems of larger trees become directly weaker compared with the structural strength of the trunk. If this is the case, the anchorage moment of Maritime pine, a tap-rooted tree, which grows in shallow soils, should also scale to the second power of tree trunk diameter. In this experiment, mechanical failure by stem breakage did not occur due to the plasticity of the stems. Of the 13-year-old trees, the seven trees that had been grafted broke at the graft site but the remaining broke at the junction between the tap root and the stem. The 17-year-old trees were not completely pulled over, but noises of roots breaking were heard and failure began to occur at the base of the tap root and lateral roots after a mean Mb of 12.75 kNm had been reached. Overall, trees failed first in compression and then in tension - wood is more resistant to rupture in tension than compression.

Stokes A., J. Ball, A.H. Fitter, P. Brain and M.P. Coutts. 1996. An experimental investigation of the resistance of model root systems to uprooting. *Annals of Botany*. 78:415-421.
This paper describes experiments on models which simulate the uprooting of a root system with different branching patterns and angles. The study was based on previous experiments that concluded that herringbone root systems (where lateral roots arise off one main axis) and symmetric distribution of laterals around the main axis make trees less vulnerable to windthrow. A first test was done on artificial root systems made out of wire in a cylinder filled with sand. Tensile testing was done as each was vertically pulled from the sand. When only a tap root existed (no laterals), it pulled out easily without cracking the soil. When two laterals existed, the soil cracked and some lifted out. When secondary lateral roots existed off main laterals, there was a significant increase in tension and resistance was enhanced at an angle less than 90 degrees. Soil shear strength was the most important factor in resisting uprooting. The ideal lateral would be 90 degrees from the tap root.

Stokes, A., A. H. Fitter, and M. P. Coutts. 1995. Responses of young trees to wind and shading - Effects on Root Architecture. *Journal of Experimental Botany*. 46:1139-1146.
Young Sitka spruce and European larch were grown from seed in two wind tunnels. The wind exposure was intermittent in order to determine influences of wind on the development of the root systems of the young trees. As a tree sways in the wind, leeward and especially windward lateral roots are placed under the most stress. Larger roots or a greater branching density in these areas will help counteract wind stresses on the tree.

Stokes, A. and C. Mattheck. 1996. Variations of wood Strength in tree roots. *Journal of Experimental Botany*. 47(298):693-699.
Evaluation of ash, larch, beech, sweet chestnut, Scots pine, poplar, and Norway spruce roots, found that root strength decreased along the root at different rates, depending on the type of root system present. Slightly tapered lateral roots in plate root systems were relatively stronger further away from the stem than the highly tapered laterals in heart and tap root systems. Wood strength in Norway spruce (plate systems) was found to increase along the lateral roots before decreasing again. The increase in strength may coincide with the point of maximum bending of the root as the tree sways back and forth in the wind.

Strength also increased on the underside of laterals in the plate systems of high compressive stresses due to the weight of the tree pushing the root on to the hard bearing surface of the soil. The study also found that the high rate of branching near the stem, or large, rigid, main tap root, found in the heart and tap root systems, respectively, allows a faster dissipation of forces nearer the stem, therefore a high investment in strength further along the root is not necessary. Lateral bending strength was found to be much greater in hardwoods than softwoods but compression strength between the two tree types was similar. Both lateral bending and compression strength of the wood decreased with increasing distance from the stem in all samples.

Stokes A., B.C. Nicoll, M.P. Coutts, and A.H. Fitter. 1997. Responses of young Sitka spruce clones to mechanical perturbation and nutrition: effects on biomass allocation, root development, and resistance to bending. *Canadian Journal of Forest Resources.* 27:1049-1057.
The influence of mechanical disturbance on the growth of Sitka spruce was examined on eight plants from each of ten clones. A flexing machine was used to apply the disturbance; plants were flexed for 196 days, with an equal number of plants not "flexed" as controls. Additionally, plants were grown at two differing nutrient regimes to determine the effect of nutrient availability on the response to mechanical stimulation. In the high-nutrient treatment, flexing had no significant effect on the shoot biomass and only a small effect on the stem height. For the low-nutrient flexed plants, the stem diameter was larger, but only along the axis of the flexing treatment. Flexing caused significant increases in coarse root mass, coarse-root-to-fine-root ratio, and total root-to-shoot ratio. Additionally, increases were seen in the mean cross-sectional area and mass of lateral flexed plants which showed an increase in vertical vs. horizontal diameter. Differences were also seen in the incidence of coarse branches, with these roots having a higher incidence than on those roots lying across the axis of flexing, or the roots from the control plants. Clonal effects were also observed in most of the growth responses measured; these responses should improve the anchorage of trees subjected to wind movement. Specifically, in pulling tests, resistance to horizontal deflection was increased in the flexed plants from the low-nutrient treatment. Overall, the shoots of Sitka spruce generally showed small but inconsistent responses to perturbation. Woody roots however, were highly responsive to flexing.

Stone, E.L. and P.J. Kalisz. 1991. On maximum extent of tree roots. *Forest Ecology and Management.* 46:59-102.
This was a survey of the literature combined with other information sources aimed at summarizing what was known about maximum vertical and lateral rooting extent in trees. Maximum vertical and radial root extents were tabulated for 49 families, 96 genera and 211 vegetation species, primarily forest trees, shrubs, and horticultural trees. The work was based upon actual reports, communications, and the author's own observations of root extent. In some cases measurements of soil water changes were used to deduce maximum root extent.

The authors state that they omitted typical or average depths whenever actual maximum were provided and common place values of less than 4.9 ft (1.5 m) for depth and 22.9 ft (7 m) for radial extent. A multi-page table summarizing the maximum root extent numerous trees species. The paper indicates that even relatively young trees can have extensive root systems; The report contains information for several tree species common to the New Orleans area (none of the data were from Louisiana) with the maximum root depth and greatest radial root length respectively as follows: slash pine (*Pinus elliotti)* 15 ft (4.6 m) and greater than 59 ft (18 m); live oak (*Quercus virginiana)* (radial root length only) 100 ft (30 m); pecan (*Carya illinoinensis)* greater than 9.8 ft (3 m) and greater than 32.8 ft (10 m); American sycamore (*Platanus occidentalis)* 6.9 ft (2.1 m) and 49.2 ft (15 m); and hackberry (*Celtis occidentalis)* 8.2 ft (2.5 m) and 41.3 ft (12.6 m).

Sudmeyer, R. A., J. Speijers and B. D. Nicholas. 2004. Root distribution of *Pinus pinaster*, *P. radiata*, *Eucalyptus globulus* and *E. kochii* and associated soil chemistry in agricultural land adjacent to tree lines. *Tree Physiol.* 24:1333-1346.
The authors quantified the extent and distribution of roots of four commonly planted tree species in agricultural land adjacent to tree lines, and examined the effect of soil type and root pruning on root morphology. The tree species are blue gum (*Eucalyptus globulus* Labill), Monterey pine (*Pinus radiata* D. Don), maritime pine (P. *pinaster* Ait. On) and Eucalyptus (*E. kochii* Maiden & Blakely subsp. *plenissima* C.A. Gardner). Root distribution in soil adjacent to tree lines was mapped by a trench profile method. The rate of decrease in root density with distance from the trees was greatest for the *Pinus spp.* and least for *E. kochii*. Two to four years after trees had been root pruned, both the lateral extent and vertical distribution of roots were similar for pruned and unpruned trees. The density of roots < 0.07 inches (< 2 mm) in diameter was greater for root-pruned trees than for unpruned trees ($P < 0.05$). The study species can compete with agricultural crops based on the lateral extent of their roots and the occurrence of greatest root density within 1.6 ft (0.5 m) of the soil surface.

Tamasi, E., A. Stokes, B. Lasserre, F. Danjon, S. Berthier, T. Fourcaud and D. Chiatante. 2005. Influence of wind loading on root system development and architecture in oak (*Quercus robur* L.) seedlings. *Trees.* 19:374-384.
Study tested the effect of wind loading on the root system of English oak (*Querucs robur*) in a ventilation system. Before their lateral roots had developed, the trees were sown in a sandy podzolic soil a circular pattern around a rotating arm that held a fan. The trees were subjected to artificial wind at a rate of 30 seconds per hour for seven months. After this time a sample was excavated and the root architecture and morphological characteristics were measured with a 3D digitizer. AMAPmod software was used to analyze the geometrical and topological data. Plants that were subjected to the artificial wind grew more numerous roots that were over twice the length as control plants but that the total volume of the root structure was not significantly different. Windward roots were

found to be more numerous (75% of the total) and longer (85% of total root length) than leeward roots but no differences were noticed in the roots perpendicular to the wind source. It was concluded that the development of the lateral root system resulted in better anchorage of the plant but that it sacrificed tap root development.

Tardieu, F. 1994. Growth and functioning of roots and of root Systems subjected to soil compaction - towards a system with multiple signaling. *Soil & Tillage Research*, 30:217-243.
The effect of soil mechanical impedance on root growth is discussed on several levels from the apex to the root system. In compact soil, root deepening is delayed and roots tend to have a clumped spatial arrangement. This change in root system architecture could cause water stress, even in relatively wet soil. As a consequence, root water status and water flux decrease, and stomatal conductance is reduced as a consequence of a chemical message originating in the roots.

Udawatta R.P. and G.S. Henderson. 2003. Root distribution relationships to soil properties in Missouri oak stands: A productivity index approach. *Soil Science Society of America Journal*, 67:1869-1878.
From abstract – This study examined the feasibility of adapting a soil-based productivity index to predict root distribution in Missouri oak stands. Roots and soil were sampled to a depth of 58.5 inches (149 cm) in 58 plots in the Missouri Ozarks and Missouri River hills. Soil pH, bulk density, and moisture holding capacity were determined by horizon, and the data were used in equations designed to quantify "sufficiency" for root growth. The resulting sufficiency values were used to calculate individual and combined soil property indices for each plot. First, sufficiency values for combined indices were calculated in three ways – multiplicative, geometric, and arithmetic. Next, the indices were derived by multiplying individual or combined sufficiency values by a root index factor, which the study found to be representative of proportional root distribution in "ideal" soil, and then summing the weighted values. Of the individual indices, soil pH explained 30% of fine root length variability and 29% of the total root length variability. Neither soil bulk density nor soil moisture explained root length variability. In fact, these properties actually reduced predictability when included in combined indices. Of the combined indices, the multiplicative-based index explained the greater percentage of root length variation than either the geometric or arithmetic based indices. However, no combined index accounted for more than 11 percent of the variation in root length distribution. This suggests that, to be usable in forestry, the soil-based productivity index needs to be refined and/or expanded to include variables such as nutrients and climate.

Wallace, D., C. Baumer, J. Dwyer, and F. Hershey. 1994. Levee armoring: woody biotechnical considerations for strengthening Midwest sevee systems. *The Restoration of Aquatic Ecosystems Symposium*, The Association of State Wetland Managers, St. Paul, Minnesota.

This paper examines the potential woody interactions with levee systems and presents some levee armoring designs. The authors concluded that instead of excluding woody vegetation, levee designs should actively incorporate woody materials as corridor plantings between the levee and river and as protective cover on the structure itself as long as inspection and flood fighting capabilities are maintained. Levee armoring with properly designed woody material will slow floodwater velocities, dissipate energy, reduce scouring potential, and increase soil shear strengths.

Watson, A. 2000. Wind-induced forces in the near-surface lateral roots of radiata pine. *Forest Ecology Management.* 135:133-142.

The goal of this paper was to determine whether relationships exist between the resistive bending moment at the base of a radiata pine tree (Monterey pine) and stresses in the near-surface lateral roots. A comparison of the forces measured in the leeward and windward roots during a storm event indicated a ratio of between 1:2 and 1:3 as the relative contribution to the strength of root anchorage provided by these roots.

Watson, A., C. Phillips and M. Marden. 1999. Root strength, growth, and rates of decay: root reinforcement changes of two tree species and their contribution to slope stability. *Plant and Soil.* 217:39–47.

Root properties of radiata pine (Monterey pine) (*Pinus radiata* D. Don) and knauka (*Kunzea ericoides* A. Rich.) were studied for their effects on slope stability and root strength. Three ages of stands were studied for each species. Maximum root depths (in apparent root zone) were 10.0 ft (3.1 m) and 7.2 ft (2.2 m) respectively for radiata pine and knauka. Maximum root lengths were 32.8 ft (10 m) for radiata pine and 20 ft (6.1 m) for knauka, although mean maximum root lengths were only 29.5 ft (9 m) and 11.8 ft (3.6 m) respectively. Re-measurement of root properties for up to four years following tree harvest showed species differences in the rate of root decay and loss of strength. Radiata pine roots began to decay almost immediately (within weeks), while knauka roots did not begin decay for up to 12 months after harvest.

Wilson, B.F. 1967. Root growth around barriers. *Botanical Gazette.* 128:79-82.

This study focused on the root growth patterns of horizontal root tips of red maple (*Acer rubrum*) when grown through a container and deflected by a root barrier. The results indicated that the roots would curve back to their original direction once they get past the barrier. The roots returned to their original direction of growth. As the angle of the barrier is increased, the amount of the recurvature increased. When roots measured where unimpeded by barriers, the roots grew straight and in the direction of the long axis of the root tip.

Wilson, A.D. and D.G. Lester. 2002. Trench inserts as long-term barriers to root transmission for control of oak wilt. *Plant Disease.* 86(10):1067-1074.

Trench inserts (root barriers) were tested as a means of reducing or preventing the spread of oak wilt through root contact among mature live oak (*Quercus virginiana)*. Barriers or trench inserts were tested for a period of seven years. Linear trenches 4.9 ft (1.5 m) deep were lined with trench insert materials. Four trench insert materials were tested, including water permeable and water-impermeable liners. Untrenched trees were used as controls and compared to trees with unlined trenches and fungicides added. Infections occurred within the first year in many of the untrenched trees, but infections were not noted until year three in any of the trees where trenches were lined with barriers. The breakout only occurred in trenched trees with the thinner water-impermeable Geomembrane 20 barrier. Over the course of the seven year study no breakouts occurred in the water permeable Biobarrier, Typar or water-impermeable Geomembrane 30 trench insert treatments. All breakouts were associated with roots that grew either over or under the trench inserts. Such breakouts were only noted in the water-impermeable trench liners. The Typar water impermeable liners were about 70% to 80% less expensive than the chemically treated, water-permeable Biobarrier liner.

Wynn, T.M., S. Mostaghimi, J.A. Burger, A.A. Harpold, M.B. Henderson and L. Henry. 2004. Variation in root density along stream banks. *Journal of Environmental Quality*. 33:2030-2039.

The study determined the type and density of vegetation that provide the greatest protection against stream bank erosion by determining the density of roots in stream banks. Root length density (RLD) with depth and aboveground vegetation density were measured. Results showed that under forested vegetation, fine roots (0.02 in < diameter < 0.07 in) or (0.5 mm < diameter < 2.0 mm) were more common throughout the bank profile, with 55% of all roots in the top 11.7 inches (30 cm). Erosion resistance has a direct relationship with fine root density; forested vegetation may provide better protection against stream bank erosion.

Ziemer, R. R. 1981. Roots and the stability of forested slopes. The International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands, *132. International. Association of Hydrological. Science. Pulication..* Christchurch, NZ. 343-361 pp.

Root decay after timber cutting can lead to slope failure. Forests clear-felled three years earlier contained about one-third of the root biomass of old-growth forests. Nearly all of the roots <0.07 inches (<2 mm) in diameter were gone from 7-year-old logged areas while about 30 percent of the <0.66 inch (<17 mm) fraction was found. If soils are barely stable with a forest cover, the loss of root strength following clear-felling can seriously affect slope stability.

Appendix 6. Personnel Resumes

Jim L. Chambers

Jim L. Chambers
Weaver Brothers Distinguished Professor of Forestry
School of Renewable Natural Resources
Louisiana State University and LSU Agricultural Center
Baton Rouge, LA
Work Phone (225) 578-4222; Fax 578-4227
e-mail: jchamb@lsu.edu

Formal Education:

Degree	Institution	Field of Study	Degree
	Univ. of Nebraska	Pre-Forestry	N/A
B.S.	Southern Ill. Univ.	Agriculture (Major, Forestry)	1970
M.S.	Southern Ill. Univ.	Forestry (Ecology)	1972
Ph.D.	Univ. of Missouri	For. (Eco-Physiology)	1976

Academic Experience:

Employer	Title	Specialization	Dates
Louisiana State Univ.	Weaver Brothers Professor of Forestry		2001- present
Louisiana State Univ.	Forestry Program Leader		2000-2005
Louisiana State Univ.	Professor	Physiology/Ecology	1999-2001
Louisiana State Univ.	Assoc. Professor	Physiology/Ecology	1981-1999
Louisiana State Univ.	Asst. Professor	Physiology/Ecology	1976-1981

Academic Assignment: Research 50%Teaching 50%

Awards, Recognition of Scholarly Achievement, Professional Societies

Xi Sigma Pi
Sigma Xi
Gamma Sigma Delta
Gamma Sigma Delta Dean's Teaching Honor Roll (1998/99, 2000/01, 2006/07)
Endowed Professorship: Weaver Brothers Distinguished Professor Forestry
Society of American Foresters
Society of Wetland Scientists
Louisiana Forestry Associatiation

Jim L. Chambers (continued)

Publications In Print:

Book Chapters, Articles in Refereed Journals, Refereed Bulletins or Refereed Proceedings;

Krauss, KW, JL Chambers, D Creech. 2007. Salt tolerance of tidal freshwater swamp species: advances using baldcypress as a model for restoration. Chapter 14 in Conner WH, Doyle TW, Krauss KW (eds) Ecology of tidal freshwater swamps of the southeastern United States (Springer Publishers, New York).

Faulkner, S.P., J.L. Chambers, W.H. Conner, R.F. Keim, J.W. Day, E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer Conservation and Use of Coastal Wetland Forests in Louisiana. 2007. Chapter 16 - in Conner WH, Doyle TW, Krauss KW (eds) Ecology of tidal freshwater swamps of the southeastern United States (Springer Publishers, New York).

Krauss, K.W., P.J. Young, J.L. Chambers, T.W. Doyle, R.R. Twilley. 2007. Sap flow characteristics of neotropical mangroves in flooded and drained soils. Tree Physiology 27, 775 783.

Lockhart, B.R. and J.L. Chambers. 2007. Cherrybark oak stump sprout survival and development five years following plantation thinning in the lower Mississippi alluvial valley, USA. New Forests 33:183 192.

Keim; R., J. L. Chambers, M. S. Hughes, L. D. Dimov, W. H. Conner, G. P. Shaffer, Emile S Gardiner, John W Day. 2006. Long-term success of stump sprouts in high-graded baldcypress-water tupelo swamps in the Mississippi Delta. Forest Ecology and Management 234:24-33.

Keim R.F., J.L. Chambers, M.S. Hughes, J.A. Nyman, C.A. Miller, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, and G.P. Shaffer. 2006. Ecological consequences of changing hydrological conditions in wetland forests of coastal Louisiana. pp. 383-395. In (ed) Y. Jun Xu. Coastal Environment and Water Quality. Water Resources Publications. Highlands Ranch, CO. 519 p.

Chambers, J.L., Conner, W.H., Day, J.W., Faulkner, S.P., Gardiner, E.S., Hughes, M.S., Keim, R.F., King, S.L., McLeod, K.W., Miller, C.A., Nyman, J.A., and Shaffer, G.P. 2005. Conservation, protection and utilization of Louisiana's Coastal Wetland Forests. Final Report to the Governor of Louisiana from the Coastal Wetland Forest Conservation and Use Science Working Group. (special contributions from Aust, W.M., Goyer, R.A., Lenhard, G.J., Souther-Effler, R.F., Rutherford, D.A., and Kelso, W.E.). 121p.

Dimov, L.D., Chambers, J.C., Lockhart, B.R. 2005. Spatial continuity of tree attributes in bottomland hardwood forests in the southeastern United States. Forest Science 51(6): 532-540.

Tang, Z., M.A. Sword Sayer, J.L. Chambers, and J.P. Barnett. 2004. Interactive effects of fertilization and throughfall exclusion on the responses and whole-tree carbon uptake of mature loblolly pine. Canadian Journal of Botany 82:850-861.

Sword Sayer, M.A., J.C. Goelz, Chambers, J.L., Z. Tang, and T.J. Dean, J.D. Haywood, and D.J. Leduc. 2004. Long-term trends in loblolly pine productivity and stand characteristics in response to stand density and fertilization in the western gulf region. Forest Ecology and Management 192:71-96.

Jim L. Chambers (continued)

Tang, Z., Chambers, J.L., Sword, M.A., Barnett, J.P. 2003. Seasonal photosynthesis and water relations of juvenile loblolly pine relative to stand density and canopy position. Trees 17(5):424-430.

Yu Shufang, J. L. Chambers , Z. Tang and J. P. Barnett, 2003. Crown characteristics of juvenile loblolly pine 6 years after application of thinning and fertilization. Forest Ecology and Management 180(1-3) 345-352.

Burke, M. and J.L. Chambers. 2003. Root dynamics in bottomland hardwood forests of the Southeastern United States Coastal Plain. Plant and Soil 250: 141-153.

Zhou, Benzhi; Sword, Mary Anne; Chambers, Jim; Andries, Dan. 2002. Monitoring new root dynamics of loblolly pine with minirhizotron technique. Forest Research, 15(3): 276-284.

Krauss, K.W., J.L. Chambers, J.A. Allen, D.M. Soileau Jr., and A.S. DeBosier. 2000. Growth and nutrition of baldcypress families planted under varying salinity regimes in Louisiana, USA. Journal of Coastal Research 16(1)153-163.

Tang, Z. J.L. Chambers, S.Guddanti, Shufang Yu and J.P. Barnett. 1999 Seasonal shoot and needle growth of loblolly pine responds to thinning fertilization and canopy position. Forest Ecology and Mgt. 120:117-130.

Krauss, K.W., J.L. Chambers, J.A. Allen, B. Luse, A. DeBosier (1999). Root and shoot responses of Taxodium distichum seedlings subjected to saline flooding. Environmental and Experimental Botany 41:15-23.

Tang, Z., J.L. Chambers, S. Guddanti, and J.P. Barnett. 1999. Thinning, fertilization, and crown position interact to control physiological responses of loblolly pine. Tree Physiology 19(2)87-94.

Chambers, J.L., D. Ward, R. Ricard, B. Stine 1999. Climate Change Impacts: Forestry and Farming. pp 45-50. In Ning, Z. N. and K.K. Abdollahi (ed.) Global Climate Change and its consequences on the Gulf Coast Region of the United States. Franklin Press, Inc. Baton Rouge and the Gulf Coast Regional Climate Change Committee.

Sword, M.A., J.L. Chambers, D.A. Gravatt, and J.D. Haywood. 1998 Ecophysiological responses of managed loblolly pine to changes in stand environment. Chapter 11, pp.185-206. In: Mickler, R.A. and S. Fox (ed.) The productivity and sustainablility of southern forest ecosystems in a changing environment. Springer Verlag, New York, NY. 892 p.

Krauss, K., J.L. Chambers and J.A. Allen. 1998. Salinity effects and differential germination of several half-sib families of baldcypress from different seed sources New Forests 15(1) 53-68.

Allen, J.A., W.H. Conner, R.A. Goyer, J.L. Chambers and K. W. Krauss. 1998. Freshwater forested wetlands and global climate change, Chapter 4, pp 33-44 in (ed) Guntenspergen, G.R. and B.A. Vairin. Vulnerability of Coastal Wetlands in the Southeastern united States: Climate Change Research Results, 1992-1997. U.S. Department of the Interior, U.S. Geological Survey. Biological Science Report. USGS/BRD/BSR-1998-0002. September 1998. 102p.

Goyer, R.A. and J.L. Chambers. 1997. Evaluation of insect defoliation in baldcypress and its relationship to flooding. National Biological Service. Biological Science Report 8. 36pp.

Gravatt, D.A., J.L. Chambers and J.P. Barnett. 1997.Temporal and spatial patterns of net photosynthesis in 12-year-old loblolly pine five growing seasons after thinning and fertilization. Forest Ecology and Management. 97:73-83.

Allen, J.A., J.L. Chambers, and S.R. Pezeshki. 1997. Effects of salinity on baldcypress seedlings: Physiological responses and their relation to salinity tolerance. Wetlands 17(2)310-320.

Jim L. Chambers (continued)

Sword, M.A. D.A. Gravatt, P.L. Faulkner and J.L. Chambers. 1996. Seasonal branch and fine root growth of juvenile loblolly pine five years after fertilization. Tree Physiology 16:899-904.

Allen, J.A., R. Pezeshki, and J.L. Chambers. 1996 Interaction of flooding and salinity stresses on baldcypress (*Taxodium distichum*). Tree Physiology vol 16(1/2)307-313.

Allen, J.A, J.L. Chambers, and D. McKinney. 1994. Intraspecific variation in the response of *Taxodium distichum* seedlings to salinity. Forest Ecology and Management 70:203-214.

Allen, J.A., J.L. Chambers, and M. Stine. 1994. Prospects for increasing the salt tolerance of forests: A review. Tree Physiology 14(7) 843-853.

Brissette, J.C. and J.L. Chambers. (1992). Leaf water status and root system water flux of shortleaf pine (Pinus echinata Mill.) seedlings are related to new root growth after transplanting. Tree Physiology 11(3)289-303.

Fralish, J.S., F.B. Crooks, J.L. Chambers, F.M. Harty. 1991. Comparison of presettlement, 2nd-growth and old-growth forest on 6 site types in the Illinois Shawnee Hills. American Midland Nat. 125(2) 294-309.

Jenkins, M. W. and J. L. Chambers. 1989. Understory light levels in mature hardwood stands after partial overstory removal. Forest Ecology and Management 26:247-256.

Pezeshki, S. R. and J. L. Chambers. 1986. Variation in flood-induced stomatal and photosynthetic responses of three bottomland tree species. Forest Sci. 32:914-923.

Pezeshki, S. R. and J. L. Chambers. 1986. Stomatal and photosynthetic response of drought-stressed cherrybark oak (Quercus falcata var. pagodefolia) and sweet gum (Liquidambar styraciflua). Can. J. For. Res. 16:841-846.

Pezeshki, S. R. and J. L. Chambers. 1986. Effects of soil salinity on stomatal conductance and photosynthesis of green ash (Fraxinus pennsylvanica Marsh.). Can. J. For. Res. 16:569-573.

Chambers, J. L., P. M. Doughtery and T. C. Hennessey. 1986. Fire: Its effects on growth and physiological processes in conifer forests. Chapter 9, p. 171-189. In. Hennessey, T. C., P. M. Doughtery, S. V. Kossuth and J. D. Johnson (ed.) Stress Physiology and Forest Productivity. Martinus Nijhoff. The Hague. The Neterlands.

Pezeshki, S. R., J. L. Chambers. 1985 b. Response of cherrybark oak seedlings to short-term flooding. Forest. Sci. 30(4):760-771.

Pezeshki, S. R. and J. L. Chambers. 1985 a. Stomatal and photosynthetic response of sweetgum (Liquidambar styraciflua L.) to flooding. Can. J. Forestry Res. 15(2):371-375.

Chambers, J. L., T. M. Hinckley, G. S. Cox, C. L. Metcalf and R. G. Aslin. 1985. Boundary-line analysis and models of leaf conductnce for four Oak-Hickory forest species. Forest Sci. 30(2):435-448.

Lassoie, J. P. and J. L. Chambers. 1976. The effects of an extreme drought on tree water status and net assimilation rates of a transplanted northern red oak under greenhouse conditions. p. 269-282. In J. S. Fralish, G. T. Weaver, and R. C. Schlesinger ed. Central Hardwood Forest Conference. Southern Illinois Univ., Carbondale, 484 p.

Phelps, J. E., J. L. Chambers and T. M. Hinckley. 1976. Some morphological ecological, and physiological traits of four Ozark forest species. p. 231-242 In J. S. Fralish, G. T. Weaver and R. C. Schlesinger ed. Central Hardwood Forest Conference, Southern Illinois University, Carbondale. 484 p.

Hinckley, T. M., J. L. Chambers, D. N. Bruckerhoff, J. E. Roberts and J. Turner. 1974. Effect of midday shading on the water relations of a white oak sapling. Can. J. of For. Res. 4(3):296-300.

Jim L. Chambers (continued)

Non-refereed Proceedings, Government and Other Publications:

Dimov, L. E. Stelzer, K. Wharton, J.S. Meadows, J.L. Chambers, K. Ribbeck, E.B. Moser. 2006. Effects of thinning intensity and crown class on cherrybark oak epicormic branching five years after treatment. Pp. 606-610. Conner, Kristina F. (ed.) Proceedings of the 13th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 640 p..

Keim, R.F., J.L. Chambers, M.S. Hughes, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, G.P. Shaffer, and L. Dimov. 2006. Long-term success of stump sprouts in baldcypress. pp. 559-563.Conner, Kristina F. (ed.) Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station..

Chambers, J.L., W.H. Conner, R.F. Keim, S.P. Faulkner, J.W. Day Jr., E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer, 2006. Towards sustainable management of Louisiana's coastal wetland forest: Problems, constraints, and a new beginning. pp. 150-157. ASABE International Conference on Forest Hydrology and Management of Forest Wetlands. Publisher, American Society of Agricultural Engineers, St. Joseph Michigan.

Chambers, J.L. 2006. Protecting coastal wetland forests: What can you do to help? Louisiana Agriculture. 49(2):4-9.

Keim, R.F., Chambers, J.L., and Dean, J. 2006. Baldcypress site relationships and silviculture. Louisiana Agriculture. 49(2):10-12.

Chambers, J.L., R.F. Keim, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J. A. Nyman, and G.P. Shaffer. 2005. Conservation of Louisiana's coastal wetland forests. pg.117-135. Louisiana Natural Resources Symposium. July 18-20, 2005 Lod Cook Conference Center, Louisiana State University, Baton Rouge, LA. 156 p. ..

Young, P .Joy, Chambers, J. L, Meadows, S. and Ribbeck, K. 2004 Radial growth of nine selected provenances under prolonged drought. p. 592. Proceedings of the 12th Biennial Southern Silvicultural Research Conference. February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Tang, Z., J.L. Chambers, S. Yu, M.A. Sword Sayer,and J.P. Barnett. 2004. Reapplication of silvicultural treatments impacts shoot growth and physiology of plantation loblolly pine. In: Proceedings of the 12th Biennial Southern Silvicultural Research Conference. pp. 450-457 February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Tang, Z., J.L. Chambers, M.A. Sword Sayer, and P. Joy Young. 2004. Long-term assessment of pine plantation productivity in Louisiana. Louisiana Agriculture 47 (3) 21-23.

Stelzer, E., Chambers, J. L, Meadows, S. and Ribbeck, K. 2004. Leaf biomass and acorn production in a thinned 30-year-old cherrybark oak (Quercus pagoda raf.) Plantation. pp. 276-279. Proceedings of the 12th Biennial Southern Silvicultural Research Conference. February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Dimov, L.D., Lockhart, B.R., Chambers, J.L. 2004. Individual oak tree growth in southern bottomland hardwood stands (preliminary results). pp.292-295Proceedings of the 12th Biennial Southern Silvicultural Research Conference. Connor, K.F. (ed.). Gen. Tech. Rep. SRS-71. Asheville, NC: USDA Forest Service, Southern Research Station..

Jim L. Chambers (continued)

Lockhart, J.L., Chambers, and K. Wharton. 2001. Stump sprouting two years after thinning in a Cherrybark oak plantation. Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22, 2001. pp. 381-385. in Oucult, K.W. (ed)Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22. 2001. Southern Research Station Gen. Tech. Rept. SRS 48..

Sword, M.A., Chambers. J.L., Z. Tang, J.C. Goelz and T.J. Dean. 2001. Long-term trends in loblolly pine productivity and stand characteristics in response to stand density and fertilization in the western gulf region. pp. 572-573 in Oucult, K.W. (ed)Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22, 2001, Southern Research Station Gen. Tech. Rept. SRS 48.

Krauss, K.W., R.A. Goyer, J.A. Allen, and J.L. Chambers. 2000. Tree shelters effective in coastal swamp restoration (Louisiana). Ecological Restoration 18(2): 200-201.

Tang, Z. J.L. Chambers, and J.P. Barnett. 1999. Characterization of optimum physiological responses of field-grown loblolly pine. Pp. 409-415. In J.D. Haywood (ed).Tenth Biennial Southern Silvicultural Research Conference. USDA-Forest Service. Southern Research Station General Technical Report SRS-30. 618p.

Yu, Shufang, Q.V. Cao, J.L. Chambers, Tang*, and J.D. Haywood. 1999. Managing leaf area for maximum volume production in a loblolly pine plantation. pp.455-460. In J.D. Haywood (ed).Tenth Biennial Southern Silvicultural Research Conference. USDA-Forest Service. Southern Research Station General Technical Report SRS-30. 618p.

Chambers, J.L., K.W. Krauss, J.A. Allen, K.Velupillai, A.S.DeBosier**, D.M. Soileau, Jr., and B. Luse**. 1998. Restoration of baldcypress in areas subjected to saltwater intrusion along the Louisiana Gulf Coast. Final report for Cooperative Agreement #1445-0004095-9104 submitted to the USDI Geological Survey, Biological Resources Division, National Wetlands Research Center, Lafayette, LA, by Louisiana State University, School of Forestry, Wildlife, and Fisheries, Baton Rouge, LA.

Allen, J.A., W.H. Conner, R.A. Goyer, J.L. Chambers, and K.W. Krauss. 1998. Chapter 4: Freshwater Forested Wetlands and Global Climate Change. pp. 33-44. In G.R. Guntenspergen and B.A. Vairin (ed). Vunerability of coastal wetlands in the southeastern United States: Climate change research results, 1992-1997.

Chambers, J.L., D. Gravatt, S.Guddanti, Z. Tang*, K. Velupillai, and J.P. Barnett. 1997. Physiological, Phenological, and Morphological Adjustments in Loblolly Pine as Related to Changes in Climate, Stand Density, and Nutrition. Final Report. USDA-FS 19-91-038. 184p.

Patterson, W.B., W.H. Hudnall, J.L. Chambers. 1996. Bottomland Hardwood Species Composition and Hydric Soil Conditions In Louisiana Agronomy Soc. Mtg. Baton Rouge, LA.

Krauss, K.W., J.L. Chambers, and J.A. Allen. 1996. Intraspecific variation in the physiological response of baldcypress (Taxodium distichum (L.) Rich.) to rapid influx of saltwater. pp. 183- 189. In Flynn, K. M. (ed) Proc. Southern Forested Wetlands Ecology and Management Conference. Clemson, South Carolina. March 25-27, 1996. 232p.

Stine, M., J.L. Chambers, M. Wilson** and K. Ribbeck. 1995. Twenty-year survival and growth of six bottomland hardwood species. pp. 500-502 USDA-FS South.Res. Stat. General Technical Rept. SRS-1. 633p.

Jim L. Chambers (continued)

Patterson, W.B., W.H. Hudnall. and J.L. Chambers 1995. Assessment of wetland hydrology and hydric soil conditions in bottomland hardwoods. pp.85-89. In (Selim, H.M. and W.H. Brown. ed) Proc. Conference on Environmental Issues. Held July 24-25, 1995, LSU Agricultural Center, Baton Rouge, LA.

Patterson, W.B., W.H. Hudnall, and J.L. Chambers 1995.Hydric soil conditions of bottomland hardwood forests and implications for wetland delineation. Proc. Of Louisiana Association of Agronomists 37:58-63.

Goyer, R.A. and J.L. Chambers. 1994. Evaluation of insect herbivory in baldcypress and its relationship to flooding. Final Report FWS 14-16-0009-91-956. USFWS, Wetlands Research Center, Lafayette. LA. 50pp.

Chambers, J.L. 1994. Physiological, phenological, and morphological adjustments in Loblolly Pine as related to changes in climate, stand density, and nutrition. Proc. Southern Global Change Meeting. Held in New Orleans. March 1-3, 1994.

Chambers, J.L., K. Velupillai, S. Guddanti, H. Williams, S. Erwin, R. Pezeshki*, and H.E. Kennedy, JR. 1993. Root growth response of several bottomland oak species to flooding. Final Report: Cooperative Research Project #19-88-064. USDA Forest Service, Southern Hardwoods Laboratory, Southern Forest Experiment Station, Stonevile, MS. 124pp.

Brissette, John C., and J.L. Chambers. 1992. Root zone environment, root growth, and water relations during seedling establishment. pp. 67-76. In Proceeding of the Shortleaf Pine Workshop, Little Rock, Arkansas. Held Oct. 29-31, 1991. USDA-FS General Tech. Rpt. SO-90. p.263

Chambers, J. L., and M. W. Henkel. 1989. Survival of natural and artificial regeneration in bottomland hardwood stands after partial overstory removal. pp. 277-283. In Proceedings of the Fifth Biennial Silviculture Research Conference. Held November 1-3, 1988. Memphis, TN. USDA-FS. Southern Forest Expt. Station, General Tech. Report. SO-74. 618 p.

Chambers, J. L., S. R. Pezeshki* and E. Du. 1988. Waterlogging and drought reduce root and shoot growth of bottomland tree species through changes in physiological responses. Poster paper presented at The International Forested Wetlands Resource: Identification and Inventory Conference. Held September 19-22, 1988. Louisiana State University, Baton Rouge, LA. Sponsored by IUFRO.

Chambers, J. L., R. G. Paul Clifton, and J. P. Barnett. 1988. Sand culture and raised beds for inducement of water tress in seedling physiology studies. pp. 164-168. Proceedings on 10th N. Am. Forest Biology Workshop held in Vancouver, British Columbia. July 1988. 364 p.

Chambers, J. L., H. C. Stuhlinger and R. G. P. Clifton. 1987. Regeneration of bottomland hardwood sites by pre-harvest planting. pp. 125-128. In Southern Silviculture Research Conference Proc. Held Nov. 4-6, 1986. Atlanta, GA.

Chambers, Jim L. and Michael W. Jenkins. 1983. Understory Light Intensity in Bottomland Hardwood Stands. p. 161-165 In (Ed) Earl P. Jones, Jr. Proceeding of 2nd Biennial Southern Silviculture Research Conference. USDA-Forest Service. Southeastern Forest Expt. Stat. General Technical Report SE-24. 513 p.

Chambers, Jim L. and Nancy L. Young. 1982. Phenology of Plantation-Grown Sweetgum, Yellow-Poplar and Cherrybark Oak. p. 161-165 In Proceeding of the 7th North American Forest Biology Workshop. Held July 26-28, 1982 at Lexington, Kentucky. 467 p.

Chambers, J. L. and James D. Smith. 1982. Effects of defoliation by the Forest Tent caterpillar on growth and leaf surface area of potted sweetgum seedlings. La. State Univ. Forestry Notes No. 135. 3 p.

Jackson, Ben D. and J.L. Chambers. (ed.) 1981. Timber harvesting in wetlands. Proc. 30th Ann. L.S.U. Forestry Symposium., La. State Univ. Div. Contin. Educ. Baton Rouge. La. 166 p.

Chambers, J. L. and C. M. Rincon. 1980. Vegetation damage associated with salt mining operations at Avery Island, La. Proc. of La. Acad. Sci. Vol. XLIII.

Chambers, J. L. and C. R. Villarrubia. 1980. An assessment of the affects of crown scorch on loblolly pine growth and survival. La. State Univ. Forestry Note No. 131. 2 p.

Fralish, J. S., S. M. Jones, R. K. O'Dell and J. L. Chambers. 1978. The effect of soil moisture on site productivity and forest composition in the Shawnee Hills of southern Illinois. p. 263-285 In Proc. Soil Moisture and Site Productivity Conf. U.S.D.A. Forest Service S&P For. Myrtle Beach, S.C., Nov. 1-3, 1977. 196 p.

Teskey, R. O., J. L. Chambers, G. S. Cox, T. M. Hinckley and J. E. Roberts. 1978. A severe drought: I. Soil-Site Relationships in an oak-hickory forest. p. 316-324 In Soil Moisture and Site Productivity Symposium, Myrtle Beach, S. C., Nov. 1-3, 1977. 196 p.

Berkoben, P. L., J. R. Toliver, J. L. Chambers, R. C. Sparks, B. R. Chandler, and G. LeBlanc. 1978. An inexpensive, easily constructed, truck-mounted ladder for use in forestry. La. State Univ. Forestry Note 126. 3 p.

Choong, E.T. and J.L. Chambers. (ed.) 1978. Energy and the southern forest. Proc. 27th Ann. L.S.U. Forestry Symp., Lousiana. State Univ. Div. Contin. Educ. Baton Rouge. 170 p.

Creative Contributions;

Co-developer of *GSRoot* (with Suresh Guddanti) a computer software program which provides measurements of plant root systems, including root length, diameter classification, and number of root tips from scanned images. This program was marketed commercially in the U.S. and abroad by PP Systems of Haverhill, Maine.

Research Grants and Contracts (Funded)

Mature tree response to hurricanes in northern Gulf Coast communities. PIs Hallie Dozier and Jim L. Chambers. Funding Source: USDA Forest Service (National Urban . Duration: Spring 2006 – Fall 2009. Requested and Awarded $68,364

Science to Establish Interim Guidelines for Coastal Wetland Forest Harvesting, Regeneration, Establishment and Protection. Jim L. Chambers and P. Joy Young. Funding Source: Governor's Office, State of Louisiana, Duration: Jan.-Dec. 2004. Funds requested: $69,278, Amount Funded. $69,278

Water Flux at different levels of scale in a Loblolly Pine stand PI's Jim L. Chambers and Zhemin Tang. Funding Source: USDA-FS. Duration: 2yrs. Funds requested: $166,759 Funded at $166,759.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase IV. Source: USDA Forest Service. Duration: FY2001. Amount Funded: $59,984.

Evaluation of Increased Tree and Branch Mortality in Louisiana. Source: CLECO, Central Louisiana Electric Cooperative. PI's Jim Chambers and Joy Young. Duration: 12-01-00 to 05-30-00. Amount Funded: $27,392.

Jim L. Chambers (continued)

Water Flux at Different Levels of Scale Within a Loblolly pine Stand as a Function of Environmental and Ccultural Practices. PI's Jim L. Chambers, Q.V. Cao, S. Guddanti, Z.M. Tang, and S. Yu.. Funding Source: USDA-Forest Service. Duration: 8/01/01 to 9/30/03. Funds requested. S$72,745. Amount Funded: $72,745

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase III. Funding Source: USDA Forest Service. Duration: FY2000. Requested: $88,293. Amount Funded: $88,293.

Tree Ring Properties and Environmental Interaction Evaluation Laboratory (TREE Lab). (Co-PI's Qinglin Wu and Joy Young). Funding Source: Louisiana Board of Regents. Duration: 2000.. Requested: $178,023. Amount Funded: $48,000.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase II. Funding Source: USDA Forest Service. Duration: FY1999. Requested: $99,152. Amount Funded: $99,152.

Understanding Bottomland Hardwood Responses to an Operational Thinning. Funding Source: Louisiana Department of Wildlife and Fisheries. Duration: July 1998 December 2000. Funds Requested: $36,000. Amount Funded: $36,000.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase I. Funding Source: USDA Forest Service. Duration: April 1998 - September 1998. Requested Yr. 1: $86,970. Amount Funded: $86,970.

Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments III. (Extended) Funding Source: USDA Forest Service. Duration: March 1997 to December 1998. Amount Funded: $118,296.

Restoration of baldcypress in areas subjected to saltwater intrusion and altered flooding regimes along the Gulf coast. Funding Source: USDI National Biological Service. Duration: May 1995 to June 1997. Amount Funded: $26,200.

Assessment of Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments II. (Extended) Funding Source: USDA Forest Service. Duration: October 1995 to September 1996. Amount Funded: $124,411

Assessment of Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments. Funding Source: USDA Forest Service. Duration: March 1995 to September 1996. Amount Funded: $68,980.

Physiological, Phenological, and Morphological Adjustments in Loblolly Pine as Related to Changes in Climate, Stand Density, and Nutrition. Funding Source: USDA Forest Service. Duration: May 20, 1991 to December 30, 1995. Amount Funded: $204,000.

Evaluation of Herbivory in Baldcypress and Its Relationship to Flooding. Funding Source: USDI FWS. Duration: June 17, 1991 to January 1994. Amount Funded: $30,000. With Richard A. Goyer.

Root Growth Response of Several Bottomland Oak Species to Flooding. Funding Source: USDA-Forest Service. Duration: August 1988 to August 1991. Amount: $47,400.

Jim L. Chambers (continued)

Regeneration of Bottomland Hardwoods by Underplanting. Funding Source: Williams Inc. Duration: January 30, 1984-December 30, 1988. Amount: $2,500.

Effects of Cultural Practices On Tree Freshness and Needle Retention in Virginia Pine. Funding Source: Louisiana-Mississippi Christmas Tree Growers Association. Duration: April 1986-1987. Amount Funded: $6,000.

Screening Transplanted, Container-Grown Loblolly Pine Seedlings for Growth and Survival Based on Physiological Responses. Funding Source: USDA-Forest Service. Duration: October 1984-January 1988. Amount Funded: $19,100.

Variation in Drought Response among Half-Sib Families of Shortleaf Pine. Funding Source: USDA-Forest Service. Duration: October 1987-September 1988. Amount Funded: $10,000.

Physiological Responses of Selected Bottomland Tree Species to Flooding. Funding Source: LSU, College of Agriculture Basic Research Grant. Duration: July 1, 1984-June 30, 1985. Amount Funded: $4,250.

Salt Fall and the Genetic Resistance of Live Oak to Saline Conditions. Funding Source: International Salt Company. Duration: 1979-1985. Amount Funded: $20,000.

Salinity and Vegetation Damage. Funding Source: International Salt Company. Duration: 1977-1978. Amount: $5,800 plus $11,000 in direct New Equipment Donations.

Thomas Joseph Dean

Thomas Joseph Dean
School of Renewable Natural Resources
Louisiana State University
Baton Rouge, LA 70803
Phone: (225) 578-4216; Fax: (225) 578-4227; e-mail: fwdean@lsu.edu

Education:

University of Oklahoma, Chemical Engineering, no degree
Oklahoma State University, Agriculture (Forestry, Science option), B.S., 1977
University of Missouri, Forestry, M.S., 1981
Thesis: "The Tolerance of Black Walnut"
Utah State University, Forest Ecology, Ph.D., 1986
Dissertation: "Stem Mechanics as a Theoretical Basis for the Self-thinning Rule"

Professional experience:

1991-Present: Professor (2004-), Associate Professor (1996-2004), Assistant Professor (1991-1996), Quantitative Silviculture, Louisiana State University A&M and LSU Agricultural Center, Baton Rouge, Louisiana

2000-Present: Adjunct Professor, Department of Forestry, Mississippi State University, Mississippi State, MS

1987-1991: Assistant Research Scientist, Department of Forestry, University of Florida, Gainesville, Florida

1986-1987: Postdoctoral Fellowship, Department of Forest Resources, Utah State University, Logan, Utah

1983-1986: Graduate Research Assistant, Department of Forest Resources, Utah State University, Logan, Utah

1981-1983: Research Technician, Department of Range Science, Utah State University, Logan, Utah

1980: Special Research Project Coordinator, Southern Forest Research Center, Weyerhaeuser Company, Hot Springs, Arkansas

1978-1981: Graduate Research Assistant, School of Forestry, Fisheries, and Wildlife, University of Missouri, Columbia, Missouri

Honors, awards, and memberships in professional societies and trade associations:

Xi Sigma Pi
Sigma Xi
Departmental Fellowship, Utah State University
Society of American Foresters
Louisiana Forestry Association
Gamma Sigma Delta Teaching Merit Honor Roll (1996, 1999, 2000)

Grants received:

Nutrient supply and demand: relationship to long-term soil productivity, silviculture, and forest floor management. Coprinicpal investigator. Agenda 2020 Sustainable Forestry Research Program, USDA Forest Service. Other investigators: D.A. Scott (FS) (PI), M.A. Sword-Sayer (FS), J.P Barnett (FS), R.A. Newbold (LA Tech University). $375,000 subcontract to LSU AgCenter $145,500. 2005-2008

Monitoring soil productivity and environmental quality in second rotation southern pine plantations: a research, industry, and university cooperative. USDA Forest Service Challenge Grant. Principal investigator (1997-2005), Coprincipal investigator (1994-1996) Other investigators M.C. Carter (PI, 1994-1996) $533,000 (summation of annual awards) 1994-2005.

Development of procedures for intensive stand-level inventories combining LiDAR and spectral remote sensing tools with traditional inventory approaches. Mississippi State University Remote Sensing Technology Center. Coprincipal Investigator. Other investigators: D.L. Evans, S.D. Roberts, R.C. Parker, and I.A. Munn (Mississippi State University); Q.V. Cao (LSU AgCenter). $288,699.54 subcontract to LSU AgCenter $60,503. 2002-2004.

Producing an interactive knowledge base for pine regeneration for the Louisiana Forestry Productivity Program. Louisiana Department of Agriculture and Forestry. Principal Investigator. Co-principal investigators: M. Dunn and M. Chamberlain. $370,303.00. 2001-2006.

Enhancing lidar-based estimates of forest stand structure through incorporation of low-altitude hyperspectral imagery. Remote Sensing Technology Center at Mississippi State University. Coprincipal Investigator, Other investigators: S.D. Roberts and D. Evans (Mississippi State University). $112,350 for two years; subcontract to LSU Ag Ctr $8,400. 2000.

Enhancement of Forestry, Wildlife, and Fisheries education through technology. LSU Student Technology Fee Disciple Specific Grant. Coprincipal Investigator. Other investigators: J.L. Chambers (PI), Q.V. Cao; R. Vlosky. $92,550. 1999

Leaf area and volume estimates in loblolly pine forests derived from aerial imaging LIDAR. NASA. Coprincipal Investigator. $278,961 for two years; subcontract to LSU Ag Ctr $52,430.00. 1999-2001.

Comparative Effects of thinning on residual stand structure and growth. USDA Forest Service Cooperative Agreement. 1997-2000. Principal Investigator. $23,000.00. 1997-2000.

Evaluation of reforestation techniques for converted wetlands in the Lower Mississippi Alluvial Valley. USGS Biological Survey Research Work Order. Principal Investigator. $30,000.00. 1993-1994.

Climate change effects on forest biomass and growth: establishing a baseline using size--density relations. USDA Forest Service Cooperative Agreement. 1992-1995. Principal Investigator. $12,500.00. 1992-1995.

Response of slash pine families to acidic precipitation and ozone stress in North Florida. USDA Forest Service Cooperative Agreement. 1987-1992. Coprincipal Investigator. $1,404,000.00. 1987-1992.

Editorial boards:

2002-present Associate Editor, Silviculture (pine), Southern Journal of Applied Forestry

2002-present Editorial board, Forest Ecology and Management

Publications (underlined names: graduate students, postdoctoral researchers, and employees):

Peer-reviewed

Cao, Q.V. and T.J. Dean. 2008. Using segmented regression to model the density–size relationship in direct-seeded slash pine stands. Forest Ecology and Management *in press.*

Dicus, C.A. and T.J. Dean. 2008. Tree-soil interactions affect production of loblolly and slash pine. Forest Science *in press.*

Scott, D.A. and **T.J. Dean.** 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. Biomass and Bioenergy 130:001-1010

Carter, M.C., **T.J. Dean**, Z. Wang, R.A. Newbold, and T. Cooksey. 2006. Impacts of harvesting and post-harvest treatments on soil bulk density, soil strength, and early growth of *Pinus teada* L.: an LTSP affiliated study. Canadian Journal of Forest Research 36: 601-614.

Roberts, S.D., **T.J. Dean**. D.L. Evans, J.W. McCombs, R.L. Harrington, and P.A. Glass. 2005. Estimating individual tree leaf area in loblolly pine plantations using LiDAR-derived measurement of height and crown dimensions. Forest Ecology and Management 213: 54-70.

Jerez, M., **T.J. Dean**, Q.V. Cao, and S.D. Roberts. 2005. Describing leaf area distribution in loblolly pine plantations with the Johnson's S_B function. Forest Science 51: 93-101.

Long, J.N., **T.J. Dean**, and S.D. Roberts. 2004. Linkages between silviculture and ecology: examination of several important conceptual models. Forest Ecology and Management 200: 249-261 .

Sword, M.A., J.C. Goelz, J.L. Chambers, Z., Tang, **T.J. Dean**, J.D. Haywood, and D.J. Leduc. 2004. Long-term trends in loblolly pine productivity and stand characteristics in response to thinning and fertilization in the western Gulf region. Forest Ecology and Management 192:71-96.

Jerez, M., **T.J. Dean**, S.D. Roberts, and D.L. Evans. 2004. Patterns of branch permeability with crown depth among loblolly pine families differing in growth rate and crown size. Trees- Structure and Function 18: 145-150.

Appendix 6. Personnel Resumes

Jim L. Chambers

Jim L. Chambers
Weaver Brothers Distinguished Professor of Forestry
School of Renewable Natural Resources
Louisiana State University and LSU Agricultural Center
Baton Rouge, LA
Work Phone (225) 578-4222; Fax 578-4227
e-mail: jchamb@lsu.edu

Formal Education:

Degree	Institution	Field of Study	Degree
	Univ. of Nebraska	Pre-Forestry	N/A
B.S.	Southern Ill. Univ.	Agriculture (Major, Forestry)	1970
M.S.	Southern Ill. Univ.	Forestry (Ecology)	1972
Ph.D.	Univ. of Missouri	For. (Eco-Physiology)	1976

Academic Experience:

Employer	Title	Specialization	Dates
Louisiana State Univ.	Weaver Brothers Professor of Forestry		2001 - present
Louisiana State Univ.	Forestry Program Leader		2000-2005
Louisiana State Univ.	Professor	Physiology/Ecology	1999-2001
Louisiana State Univ.	Assoc. Professor	Physiology/Ecology	1981-1999
Louisiana State Univ.	Asst. Professor	Physiology/Ecology	1976-1981

Academic Assignment: Research 50%Teaching 50%

Awards, Recognition of Scholarly Achievement, Professional Societies

Xi Sigma Pi
Sigma Xi
Gamma Sigma Delta
Gamma Sigma Delta Dean's Teaching Honor Roll (1998/99, 2000/01, 2006/07)
Endowed Professorship: Weaver Brothers Distinguished Professor Forestry
Society of American Foresters
Society of Wetland Scientists
Louisiana Forestry Associatiation

Jim L. Chambers (continued)
Publications In Print:

Book Chapters, Articles in Refereed Journals, Refereed Bulletins or Refereed Proceedings;

Krauss. KW. JL Chambers, D Creech. 2007. Salt tolerance of tidal freshwater swamp species: advances using baldcypress as a model for restoration. Chapter 14 in Conner WH, Doyle TW, Krauss KW (eds) Ecology of tidal freshwater swamps of the southeastern United States (Springer Publishers, New York).

Faulkner, S.P., J.L. Chambers, W.H. Conner, R.F. Keim, J.W. Day, E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer Conservation and Use of Coastal Wetland Forests in Louisiana. 2007, Chapter 16 - in Conner WH, Doyle TW, Krauss KW (eds) Ecology of tidal freshwater swamps of the southeastern United States (Springer Publishers, New York).

Krauss, K.W., P.J. Young, J.L. Chambers, T.W. Doyle, R.R. Twilley. 2007. Sap flow characteristics of neotropical mangroves in flooded and drained soils. Tree Physiology 27, 775–783.

Lockhart, B.R. and J.L. Chambers. 2007. Cherrybark oak stump sprout survival and development five years following plantation thinning in the lower Mississippi alluvial valley, USA. New Forests 33:183- 192.

Keim; R., J. L. Chambers, M. S. Hughes, L. D. Dimov, W. H. Conner, G. P. Shaffer, Emile S Gardiner, John W Day. 2006. Long-term success of stump sprouts in high-graded baldcypress-water tupelo swamps in the Mississippi Delta. Forest Ecology and Management 234:24-33.

Keim R.F., J.L. Chambers, M.S. Hughes, J.A. Nyman, C.A. Miller, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, and G.P. Shaffer. 2006. Ecological consequences of changing hydrological conditions in wetland forests of coastal Louisiana. pp. 383-395. In (ed) Y. Jun Xu. Coastal Environment and Water Quality. Water Resources Publications. Highlands Ranch, CO. 519 p.

Chambers, J.L., Conner, W.H., Day, J.W., Faulkner, S.P., Gardiner, E.S., Hughes, M.S., Keim, R.F., King, S.L., McLeod, K.W., Miller, C.A., Nyman, J.A., and Shaffer, G.P. 2005. Conservation, protection and utilization of Louisiana's Coastal Wetland Forests. Final Report to the Governor of Louisiana from the Coastal Wetland Forest Conservation and Use Science Working Group. (special contributions from Aust, W.M., Goyer, R.A., Lenhard, G.J., Souther-Effler, R.F., Rutherford, D.A., and Kelso, W.E.). 121p.

<u>Dimov</u>, L.D., Chambers, J.C., Lockhart, B.R. 2005. Spatial continuity of tree attributes in bottomland hardwood forests in the southeastern United States. Forest Science 51(6): 532-540.

Tang, Z., M.A. Sword Sayer, J.L. Chambers, and J.P. Barnett. 2004. Interactive effects of fertilization and throughfall exclusion on the responses and whole-tree carbon uptake of mature loblolly pine. Canadian Journal of Botany 82:850-861.

Sword Sayer, M.A., J.C. Goelz, Chambers, J.L., Z. Tang, and T.J. Dean, J.D. Haywood, and D.J. Leduc. 2004. Long-term trends in loblolly pine productivity and stand characteristics in response to stand density and fertilization in the western gulf region. Forest Ecology and Management 192:71-96.

Jim L. Chambers (continued)

Tang, Z., Chambers, J.L., Sword, M.A., Barnett, J.P. 2003. Seasonal photosynthesis and water relations of juvenile loblolly pine relative to stand density and canopy position. Trees 17(5):424-430.

Yu Shufang, J. L. Chambers , Z. Tang and J. P. Barnett. 2003. Crown characteristics of juvenile loblolly pine 6 years after application of thinning and fertilization. Forest Ecology and Management 180(1-3) 345-352.

Burke, M. and J.L. Chambers. 2003. Root dynamics in bottomland hardwood forests of the Southeastern United States Coastal Plain. Plant and Soil 250: 141-153.

Zhou, Benzhi; Sword, Mary Anne; Chambers, Jim; Andries, Dan. 2002. Monitoring new root dynamics of loblolly pine with minirhizotron technique. Forest Research, 15(3): 276-284.

Krauss, K.W., J.L. Chambers, J.A. Allen, D.M. Soileau Jr., and A.S. DeBosier. 2000. Growth and nutrition of baldcypress families planted under varying salinity regimes in Louisiana, USA. Journal of Coastal Research 16(1)153-163.

Tang, Z. J.L. Chambers, S.Guddanti, Shufang Yu and J.P. Barnett. 1999 Seasonal shoot and needle growth of loblolly pine responds to thinning fertilization and canopy position. Forest Ecology and Mgt. 120:117-130.

Krauss, K.W., J.L. Chambers, J.A. Allen, B. Luse, A. DeBosier (1999). Root and shoot responses of Taxodium distichum seedlings subjected to saline flooding. Environmental and Experimental Botany 41:15-23.

Tang, Z., J.L. Chambers, S. Guddanti, and J.P. Barnett. 1999. Thinning, fertilization, and crown position interact to control physiological responses of loblolly pine. Tree Physiology 19(2)87-94.

Chambers, J.L., D. Ward, R. Ricard, B. Stine 1999. Climate Change Impacts: Forestry and Farming. pp 45-50. In Ning, Z. N. and K.K. Abdollahi (ed.) Global Climate Change and its consequences on the Gulf Coast Region of the United States. Franklin Press, Inc. Baton Rouge and the Gulf Coast Regional Climate Change Committee.

Sword, M.A., J.L. Chambers, D.A. Gravatt, and J.D. Haywood. 1998 Ecophysiological responses of managed loblolly pine to changes in stand environment. Chapter 11, pp.185-206. In: Mickler, R.A. and S. Fox (ed.) The productivity and sustainablility of southern forest ecosystems in a changing environment. Springer Verlag, New York, NY. 892 p.

Krauss, K., J.L. Chambers and J.A. Allen. 1998. Salinity effects and differential germination of several half-sib families of baldcypress from different seed sources New Forests 15(1) 53-68.

Allen, J.A., W.H. Conner, R.A. Goyer, J.L. Chambers and K. W. Krauss. 1998. Freshwater forested wetlands and global climate change, Chapter 4, pp 33-44 in (ed) Guntenspergen, G.R. and B.A. Vairin. Vulnerability of Coastal Wetlands in the Southeastern united States: Climate Change Research Results, 1992-1997. U.S. Department of the Interior, U.S. Geological Survey. Biological Science Report. USGS/BRD/BSR-1998-0002. September 1998. 102p.

Goyer, R.A. and J.L. Chambers. 1997. Evaluation of insect defoliation in baldcypress and its relationship to flooding. National Biological Service. Biological Science Report 8. 36pp.

Gravatt, D.A., J.L. Chambers and J.P. Barnett. 1997.Temporal and spatial patterns of net photosynthesis in 12-year-old loblolly pine five growing seasons after thinning and fertilization. Forest Ecology and Management. 97:73-83.

Allen, J.A., J.L. Chambers, and S.R. Pezeshki. 1997. Effects of salinity on baldcypress seedlings: Physiological responses and their relation to salinity tolerance. Wetlands 17(2)310-320.

Jim L. Chambers (continued)

Sword, M.A. D.A. Gravatt, P.L. Faulkner and J.L. Chambers. 1996. Seasonal branch and fine root growth of juvenile loblolly pine five years after fertilization. Tree Physiology 16:899-904.

Allen, J.A., R. Pezeshki, and J.L. Chambers. 1996 Interaction of flooding and salinity stresses on baldcypress (*Taxodium distichum*). Tree Physiology vol 16(1/2)307-313.

Allen, J.A, J.L. Chambers, and D. McKinney. 1994. Intraspecific variation in the response of *Taxodium distichum* seedlings to salinity. Forest Ecology and Management 70:203-214.

Allen, J.A., J.L. Chambers, and M. Stine. 1994. Prospects for increasing the salt tolerance of forests: A review. Tree Physiology 14(7) 843-853.

Brissette, J.C. and J.L. Chambers. (1992). Leaf water status and root system water flux of shortleaf pine (Pinus echinata Mill.) seedlings are related to new root growth after transplanting. Tree Physiology 11(3)289-303.

Fralish, J.S., F.B. Crooks, J.L. Chambers, F.M. Harty. 1991. Comparison of presettlement, 2nd-growth and old-growth forest on 6 site types in the Illinois Shawnee Hills. American Midland Nat. 125(2) 294-309.

Jenkins, M. W. and J. L. Chambers. 1989. Understory light levels in mature hardwood stands after partial overstory removal. Forest Ecology and Management 26:247-256.

Pezeshki, S. R. and J. L. Chambers. 1986. Variation in flood-induced stomatal and photosynthetic responses of three bottomland tree species. Forest Sci. 32:914-923.

Pezeshki, S. R. and J. L. Chambers. 1986. Stomatal and photosynthetic response of drought-stressed cherrybark oak (Quercus falcata var. pagodefolia) and sweet gum (Liquidambar styraciflua). Can. J. For. Res. 16:841-846.

Pezeshki, S. R. and J. L. Chambers. 1986. Effects of soil salinity on stomatal conductance and photosynthesis of green ash (Fraxinus pennsylvanica Marsh.). Can. J. For. Res. 16:569-573.

Chambers, J. L., P. M. Doughtery and T. C. Hennessey. 1986. Fire: Its effects on growth and physiological processes in conifer forests. Chapter 9, p. 171-189. In. Hennessey, T. C., P. M. Doughtery, S. V. Kossuth and J. D. Johnson (ed.) Stress Physiology and Forest Productivity. Martinus Nijhoff. The Hague. The Neterlands.

Pezeshki, S. R., J. L. Chambers. 1985 b. Response of cherrybark oak seedlings to short-term flooding. Forest. Sci. 30(4):760-771.

Pezeshki, S. R. and J. L. Chambers. 1985 a. Stomatal and photosynthetic response of sweetgum (Liquidambar styraciflua L.) to flooding. Can. J. Forestry Res. 15(2):371-375.

Chambers, J. L., T. M. Hinckley, G. S. Cox, C. L. Metcalf and R. G. Aslin. 1985. Boundary-line analysis and models of leaf conductnce for four Oak-Hickory forest species. Forest Sci. 30(2):435-448.

Lassoie, J. P. and J. L. Chambers. 1976. The effects of an extreme drought on tree water status and net assimilation rates of a transplanted northern red oak under greenhouse conditions. p. 269-282. In J. S. Fralish, G. T. Weaver, and R. C. Schlesinger ed. Central Hardwood Forest Conference. Southern Illinois Univ., Carbondale, 484 p.

Phelps, J. E., J. L. Chambers and T. M. Hinckley. 1976. Some morphological ecological, and physiological traits of four Ozark forest species. p. 231-242 In J. S. Fralish, G. T. Weaver and R. C. Schlesinger ed. Central Hardwood Forest Conference. Southern Illinois University, Carbondale. 484 p.

Hinckley, T. M., J. L. Chambers, D. N. Bruckerhoff, J. E. Roberts and J. Turner. 1974. Effect of midday shading on the water relations of a white oak sapling. Can. J. of For. Res. 4(3):296-300.

Jim L. Chambers (continued)

Non-refereed Proceedings, Government and Other Publications:

Dimov, L. E. Stelzer, K. Wharton, J.S. Meadows, J.L. Chambers, K. Ribbeck, E.B. Moser. 2006. Effects of thinning intensity and crown class on cherrybark oak epicormic branching five years after treatment. Pp. 606-610. Conner, Kristina F. (ed.) Proceedings of the 13th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 640 p..

Keim, R.F., J.L. Chambers, M.S. Hughes, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, G.P. Shaffer, and L. Dimov. 2006. Long-term success of stump sprouts in baldcypress. pp. 559-563.Conner, Kristina F. (ed.) Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station..

Chambers, J.L.. W.H. Conner, R.F. Keim, S.P. Faulkner, J.W. Day Jr., E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer. 2006. Towards sustainable management of Louisiana's coastal wetland forest: Problems, constraints, and a new beginning. pp. 150-157. ASABE International Conference on Forest Hydrology and Management of Forest Wetlands. Publisher. American Society of Agricultural Engineers, St. Joseph Michigan.

Chambers, J.L. 2006. Protecting coastal wetland forests: What can you do to help? Louisiana Agriculture. 49(2):4-9.

Keim, R.F., Chambers, J.L., and Dean, J. 2006. Baldcypress site relationships and silviculture. Louisiana Agriculture. 49(2):10-12.

Chambers, J.L., R.F. Keim, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J. A. Nyman, and G.P. Shaffer. 2005. Conservation of Louisiana's coastal wetland forests. pg.117-135. Louisiana Natural Resources Symposium. July 18-20, 2005 Lod Cook Conference Center, Louisiana State University. Baton Rouge, LA. 156 p. ..

Young, P .Joy, Chambers, J. L, Meadows, S. and Ribbeck, K. 2004 Radial growth of nine selected provenances under prolonged drought. p. 592. Proceedings of the 12th Biennial Southern Silvicultural Research Conference. February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Tang, Z., J.L. Chambers, S. Yu, M.A. Sword Sayer,and J.P. Barnett. 2004. Reapplication of silvicultural treatments impacts shoot growth and physiology of plantation loblolly pine. In: Proceedings of the 12th Biennial Southern Silvicultural Research Conference. pp. 450-457 February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Tang, Z., J.L. Chambers, M.A. Sword Sayer, and P. Joy Young. 2004. Long-term assessment of pine plantation productivity in Louisiana. Louisiana Agriculture 47 (3) 21-23.

Stelzer, E., Chambers, J. L, Meadows, S. and Ribbeck, K. 2004. Leaf biomass and acorn production in a thinned 30-year-old cherrybark oak (Quercus pagoda raf.) Plantation. pp. 276-279. Proceedings of the 12th Biennial Southern Silvicultural Research Conference. February 25-27, 2003, Biloxi, MS. Gen. Tech. Rep. SRS, Asheville, NC.

Dimov, L.D., Lockhart, B.R., Chambers, J.L. 2004. Individual oak tree growth in southern bottomland hardwood stands (preliminary results). pp.292-295Proceedings of the 12th Biennial Southern Silvicultural Research Conference. Connor, K.F. (ed.). Gen. Tech. Rep. SRS-71. Asheville, NC: USDA Forest Service, Southern Research Station..

Jim L. Chambers (continued)

Lockhart, J.L., Chambers, and K. Wharton. 2001. Stump sprouting two years after thinning in a Cherrybark oak plantation. Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22, 2001, pp. 381-385. in Oucult, K.W. (ed)Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22, 2001, Southern Research Station Gen. Tech. Rept. SRS 48..

Sword, M.A., Chambers, J.L., Z. Tang, J.C. Goelz and T.J. Dean. 2001. Long-term trends in loblolly pine productivity and stand characteristics in response to stand density and fertilization in the western gulf region. pp. 572-573 in Oucult, K.W. (ed)Eleventh Biennial Southern Silvicultural Research Conf. Knoxville, TN. March 20-22, 2001, Southern Research Station Gen. Tech. Rept. SRS 48.

Krauss, K.W., R.A. Goyer, J.A. Allen, and J.L. Chambers. 2000. Tree shelters effective in coastal swamp restoration (Louisiana). Ecological Restoration 18(2): 200-201.

Tang, Z. J.L. Chambers, and J.P. Barnett. 1999. Characterization of optimum physiological responses of field-grown loblolly pine. Pp. 409-415. In J.D. Haywood (ed).Tenth Biennial Southern Silvicultural Research Conference. USDA-Forest Service. Southern Research Station General Technical Report SRS-30. 618p.

Yu, Shufang, Q.V. Cao, J.L. Chambers, Tang*, and J.D. Haywood. 1999. Managing leaf area for maximum volume production in a loblolly pine plantation. pp.455-460. In J.D. Haywood (ed).Tenth Biennial Southern Silvicultural Research Conference. USDA-Forest Service. Southern Research Station General Technical Report SRS-30. 618p.

Chambers, J.L., K.W. Krauss, J.A. Allen, K.Velupillai, A.S.DeBosier**, D.M. Soileau, Jr., and B. Luse**. 1998. Restoration of baldcypress in areas subjected to saltwater intrusion along the Louisiana Gulf Coast. Final report for Cooperative Agreement #1445-0004095-9104 submitted to the USDI Geological Survey, Biological Resources Division, National Wetlands Research Center, Lafayette, LA, by Louisiana State University, School of Forestry, Wildlife, and Fisheries, Baton Rouge, LA.

Allen, J.A., W.H. Conner, R.A. Goyer, J.L. Chambers, and K.W. Krauss. 1998. Chapter 4: Freshwater Forested Wetlands and Global Climate Change. pp. 33-44. In G.R. Guntenspergen and B.A. Vairin (ed). Vurnerability of coastal wetlands in the southeastern United States: Climate change research results, 1992-1997.

Chambers, J.L., D. Gravatt, S.Guddanti, Z. Tang*, K. Velupillai, and J.P. Barnett. 1997. Physiological, Phenological, and Morphological Adjustments in Loblolly Pine as Related to Changes in Climate, Stand Density, and Nutrition. Final Report. USDA-FS 19-91-038. 184p.

Patterson, W.B., W.H. Hudnall, J.L. Chambers. 1996. Bottomland Hardwood Species Composition and Hydric Soil Conditions In Louisiana Agronomy Soc. Mtg. Baton Rouge, LA.

Krauss, K.W., J.L. Chambers, and J.A. Allen. 1996. Intraspecific variation in the physiological response of baldcypress (Taxodium distichum (L.) Rich.) to rapid influx of saltwater. pp. 183- 189. In Flynn, K. M. (ed) Proc. Southern Forested Wetlands Ecology and Management Conference. Clemson, South Carolina. March 25-27, 1996. 232p.

Stine, M., J.L. Chambers, M. Wilson** and K. Ribbeck. 1995. Twenty-year survival and growth of six bottomland hardwood species. pp. 500-502 USDA-FS South.Res. Stat. General Technical Rept. SRS-1. 633p.

Jim L. Chambers (continued)

Patterson. W.B., W.H. Hudnall. and J.L. Chambers 1995. Assessment of wetland hydrology and hydric soil conditions in bottomland hardwoods. pp.85-89. In (Selim, H.M. and W.H. Brown, ed) Proc. Conference on Environmental Issues. Held July 24-25, 1995, LSU Agricultural Center, Baton Rouge, LA.

Patterson, W.B., W.H. Hudnall, and J.L. Chambers 1995.Hydric soil conditions of bottomland hardwood forests and implications for wetland delineation. Proc. Of Louisiana Association of Agronomists 37:58-63.

Goyer, R.A. and J.L. Chambers. 1994. Evaluation of insect herbivory in baldcypress and its relationship to flooding. Final Report FWS 14-16-0009-91-956. USFWS. Wetlands Research Center, Lafayette. LA. 50pp.

Chambers, J.L. 1994. Physiological, phenological, and morphological adjustments in Loblolly Pine as related to changes in climate, stand density, and nutrition. Proc. Southern Global Change Meeting. Held in New Orleans, March 1-3, 1994.

Chambers, J.L., K. Velupillai, S. Guddanti, H. Williams, S. Erwin, R. Pezeshki*, and H.E. Kennedy, JR. 1993. Root growth response of several bottomland oak species to flooding. Final Report: Cooperative Research Project #19-88-064. USDA Forest Service, Southern Hardwoods Laboratory, Southern Forest Experiment Station, Stonevile, MS. 124pp.

Brissette, John C., and J.L. Chambers. 1992. Root zone environment, root growth, and water relations during seedling establishment. pp. 67-76. In Proceeding of the Shortleaf Pine Workshop, Little Rock, Arkansas. Held Oct. 29-31, 1991. USDA-FS General Tech. Rpt. SO-90. p.263

Chambers, J. L., and M. W. Henkel. 1989. Survival of natural and artificial regeneration in bottomland hardwood stands after partial overstory removal. pp. 277-283. In Proceedings of the Fifth Biennial Silviculture Research Conference. Held November 1-3, 1988. Memphis, TN. USDA-FS. Southern Forest Expt. Station, General Tech. Report. SO-74. 618 p.

Chambers, J. L., S. R. Pezeshki* and E. Du. 1988. Waterlogging and drought reduce root and shoot growth of bottomland tree species through changes in physiological responses. Poster paper presented at The International Forested Wetlands Resource: Identification and Inventory Conference. Held September 19-22, 1988. Louisiana State University, Baton Rouge, LA. Sponsored by IUFRO.

Chambers, J. L., R. G. Paul Clifton, and J. P. Barnett. 1988. Sand culture and raised beds for inducement of water tress in seedling physiology studies. pp. 164-168. Proceedings on 10th N. Am. Forest Biology Workshop held in Vancouver, British Columbia. July 1988. 364 p.

Chambers, J. L., H. C. Stuhlinger and R. G. P. Clifton. 1987. Regeneration of bottomland hardwood sites by pre-harvest planting. pp. 125-128. In Southern Silviculture Research Conference Proc. Held Nov. 4-6, 1986. Atlanta, GA.

Chambers, Jim L. and Michael W. Jenkins. 1983. Understory Light Intensity in Bottomland Hardwood Stands. p. 161-165 In (Ed) Earl P. Jones, Jr. Proceeding of 2nd Biennial Southern Silviculture Research Conference. USDA-Forest Service. Southeastern Forest Expt. Stat. General Technical Report SE-24. 513 p.

Chambers, Jim L. and Nancy L. Young. 1982. Phenology of Plantation-Grown Sweetgum, Yellow-Poplar and Cherrybark Oak. p. 161-165 In Proceeding of the 7th North American Forest Biology Workshop. Held July 26-28, 1982 at Lexington, Kentucky. 467 p.

Chambers, J. L. and James D. Smith. 1982. Effects of defoliation by the Forest Tent caterpillar on growth and leaf surface area of potted sweetgum seedlings. La. State Univ. Forestry Notes No. 135. 3 p.

Jim L. Chambers (continued)

Jackson, Ben D. and J.L. Chambers. (ed.) 1981. Timber harvesting in wetlands. Proc. 30th Ann. L.S.U. Forestry Symposium., La. State Univ. Div. Contin. Educ. Baton Rouge, La. 166 p.

Chambers, J. L. and C. M. Rincon. 1980. Vegetation damage associated with salt mining operations at Avery Island. La. Proc. of La. Acad. Sci. Vol. XLIII.

Chambers. J. L. and C. R. Villarrubia. 1980. An assessment of the affects of crown scorch on loblolly pine growth and survival. La. State Univ. Forestry Note No. 131. 2 p.

Fralish, J. S., S. M. Jones, R. K. O'Dell and J. L. Chambers. 1978. The effect of soil moisture on site productivity and forest composition in the Shawnee Hills of southern Illinois. p. 263-285 In Proc. Soil Moisture and Site Productivity Conf. U.S.D.A. Forest Service S&P For. Myrtle Beach, S.C., Nov. 1-3, 1977. 196 p.

Teskey, R. O., J. L. Chambers, G. S. Cox, T. M. Hinckley and J. E. Roberts. 1978. A severe drought: I. Soil-Site Relationships in an oak-hickory forest. p. 316-324 In Soil Moisture and Site Productivity Symposium, Myrtle Beach, S. C., Nov. 1-3, 1977. 196 p.

Berkoben, P. L, J. R. Toliver, J. L. Chambers, R. C. Sparks, B. R. Chandler, and G. LeBlanc. 1978. An inexpensive, easily constructed, truck-mounted ladder for use in forestry. La. State Univ. Forestry Note 126. 3 p.

Choong, E.T. and J.L. Chambers. (ed.) 1978. Energy and the southern forest. Proc. 27th Ann. L.S.U. Forestry Symp., Lousiana. State Univ. Div. Contin. Educ. Baton Rouge. 170 p.

Creative Contributions;

Co-developer of *GSRoot* (with Suresh Guddanti) a computer software program which provides measurements of plant root systems, including root length, diameter classification, and number of root tips from scanned images. This program was marketed commercially in the U.S. and abroad by PP Systems of Haverhill, Maine.

Research Grants and Contracts (Funded)

Mature tree response to hurricanes in northern Gulf Coast communities. PIs Hallie Dozier and Jim L. Chambers. Funding Source: USDA Forest Service (National Urban . Duration: Spring 2006 – Fall 2009. Requested and Awarded $68,364

Science to Establish Interim Guidelines for Coastal Wetland Forest Harvesting, Regeneration, Establishment and Protection. Jim L. Chambers and P. Joy Young. Funding Source: Governor's Office, State of Louisiana, Duration: Jan.-Dec. 2004. Funds requested: $69,278, Amount Funded. $69,278

Water Flux at different levels of scale in a Loblolly Pine stand PI's Jim L. Chambers and Zhemin Tang. Funding Source: USDA-FS. Duration: 2yrs. Funds requested: $166,759 Funded at $166,759.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase IV. Source: USDA Forest Service. Duration: FY2001. Amount Funded: $59,984.

Evaluation of Increased Tree and Branch Mortality in Louisiana. Source: CLECO, Central Louisiana Electric Cooperative. PI's Jim Chambers and Joy Young. Duration: 12-01-00 to 05-30-00. Amount Funded: $27,392.

Jim L. Chambers (continued)

Water Flux at Different Levels of Scale Within a Loblolly pine Stand as a Function of Environmental and Ccultural Practices. PI's Jim L. Chambers, Q.V. Cao, S. Guddanti, Z.M. Tang, and S. Yu.. Funding Source: USDA-Forest Service. Duration: 8/01/01 to 9/30/03. Funds requested. $$72,745. Amount Funded: $72,745

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase III. Funding Source: USDA Forest Service. Duration: FY2000. Requested: $88,293. Amount Funded: $88,293.

Tree Ring Properties and Environmental Interaction Evaluation Laboratory (TREE Lab). (Co-PI's Qinglin Wu and Joy Young). Funding Source: Louisiana Board of Regents. Duration: 2000.. Requested: $178,023. Amount Funded: $48,000.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase II. Funding Source: USDA Forest Service. Duration: FY1999. Requested: $99,152. Amount Funded: $99,152.

Understanding Bottomland Hardwood Responses to an Operational Thinning. Funding Source: Louisiana Department of Wildlife and Fisheries. Duration: July 1998 December 2000. Funds Requested: $36,000. Amount Funded: $36,000.

Water Flux at Different Levels of Scale within a Loblolly Pine Stand as a Function of Environment and Cultural Practices, Phase I. Funding Source: USDA Forest Service. Duration: April 1998 – September 1998. Requested Yr. 1: $86,970. Amount Funded: $86,970.

Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments III. (Extended) Funding Source: USDA Forest Service. Duration: March 1997 to December 1998. Amount Funded: $118,296.

Restoration of baldcypress in areas subjected to saltwater intrusion and altered flooding regimes along the Gulf coast. Funding Source: USDI National Biological Service. Duration: May 1995 to June 1997. Amount Funded: $26,200.

Assessment of Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments II. (Extended) Funding Source: USDA Forest Service. Duration: October 1995 to September 1996. Amount Funded: $124,411

Assessment of Global Change/Cultural Practice Effects on Loblolly Pine Ecophysiological Responses: Responses to a Second Application of Thinning and Fertilization Treatments. Funding Source: USDA Forest Service. Duration: March 1995 to September 1996. Amount Funded: $68,980.

Physiological, Phenological, and Morphological Adjustments in Loblolly Pine as Related to Changes in Climate, Stand Density, and Nutrition. Funding Source: USDA Forest Service. Duration: May 20, 1991 to December 30, 1995. Amount Funded: $204,000.

Evaluation of Herbivory in Baldcypress and Its Relationship to Flooding. Funding Source: USDI FWS. Duration: June 17, 1991 to January 1994. Amount Funded: $30,000. With Richard A. Goyer.

Root Growth Response of Several Bottomland Oak Species to Flooding. Funding Source: USDA-Forest Service. Duration: August 1988 to August 1991. Amount: $47,400.

Jim L. Chambers (continued)

Regeneration of Bottomland Hardwoods by Underplanting. Funding Source: Williams Inc. Duration: January 30, 1984-December 30, 1988. Amount: $2,500.

Effects of Cultural Practices On Tree Freshness and Needle Retention in Virginia Pine. Funding Source: Louisiana-Mississippi Christmas Tree Growers Association. Duration: April 1986-1987. Amount Funded: $6,000.

Screening Transplanted, Container-Grown Loblolly Pine Seedlings for Growth and Survival Based on Physiological Responses. Funding Source: USDA-Forest Service. Duration: October 1984-January 1988. Amount Funded: $19,100.

Variation in Drought Response among Half-Sib Families of Shortleaf Pine. Funding Source: USDA-Forest Service. Duration: October 1987-September 1988. Amount Funded: $10,000.

Physiological Responses of Selected Bottomland Tree Species to Flooding. Funding Source: LSU, College of Agriculture Basic Research Grant. Duration: July 1, 1984-June 30, 1985. Amount Funded: $4,250.

Salt Fall and the Genetic Resistance of Live Oak to Saline Conditions. Funding Source: International Salt Company. Duration: 1979-1985. Amount Funded: $20,000.

Salinity and Vegetation Damage. Funding Source: International Salt Company. Duration: 1977-1978. Amount: $5,800 plus $11,000 in direct New Equipment Donations.

Thomas Joseph Dean

Thomas Joseph Dean
School of Renewable Natural Resources
Louisiana State University
Baton Rouge, LA 70803
Phone: (225) 578-4216; Fax: (225) 578-4227; e-mail: fwdean@lsu.edu

Education:

University of Oklahoma, Chemical Engineering, no degree
Oklahoma State University, Agriculture (Forestry, Science option), B.S., 1977
University of Missouri, Forestry, M.S., 1981
Thesis: "The Tolerance of Black Walnut"
Utah State University, Forest Ecology, Ph.D., 1986
Dissertation: "Stem Mechanics as a Theoretical Basis for the Self-thinning Rule"

Professional experience:

1991-Present: Professor (2004-), Associate Professor (1996-2004), Assistant Professor (1991-1996), Quantitative Silviculture, Louisiana State University A&M and LSU Agricultural Center, Baton Rouge, Louisiana

2000-Present: Adjunct Professor, Department of Forestry, Mississippi State University, Mississippi State, MS

1987-1991: Assistant Research Scientist, Department of Forestry, University of Florida, Gainesville, Florida

1986-1987: Postdoctoral Fellowship, Department of Forest Resources, Utah State University, Logan, Utah

1983-1986: Graduate Research Assistant, Department of Forest Resources, Utah State University, Logan, Utah

1981-1983: Research Technician, Department of Range Science, Utah State University, Logan, Utah

1980: Special Research Project Coordinator, Southern Forest Research Center, Weyerhaeuser Company, Hot Springs, Arkansas

1978-1981: Graduate Research Assistant, School of Forestry, Fisheries, and Wildlife, University of Missouri, Columbia, Missouri

Honors, awards, and memberships in professional societies and trade associations:

Xi Sigma Pi
Sigma Xi
Departmental Fellowship, Utah State University
Society of American Foresters
Louisiana Forestry Association
Gamma Sigma Delta Teaching Merit Honor Roll (1996, 1999, 2000)

Grants received:

Nutrient supply and demand: relationship to long-term soil productivity, silviculture, and forest floor management. Coprinicpal investigator. Agenda 2020 Sustainable Forestry Research Program, USDA Forest Service. Other investigators: D.A. Scott (FS) (PI), M.A. Sword-Sayer (FS), J.P Barnett (FS), R.A. Newbold (LA Tech University). $375,000 subcontract to LSU AgCenter $145,500. 2005-2008

Monitoring soil productivity and environmental quality in second rotation southern pine plantations: a research, industry, and university cooperative. USDA Forest Service Challenge Grant. Principal investigator (1997-2005), Coprincipal investigator (1994-1996) Other investigators M.C. Carter (PI, 1994-1996) $533,000 (summation of annual awards) 1994-2005.

Development of procedures for intensive stand-level inventories combining LiDAR and spectral remote sensing tools with traditional inventory approaches. Mississippi State University Remote Sensing Technology Center. Coprincipal Investigator. Other investigators: D.L. Evans, S.D. Roberts, R.C. Parker, and I.A. Munn (Mississippi State University); Q.V. Cao (LSU AgCenter). $288,699.54 subcontract to LSU AgCenter $60,503. 2002-2004.

Producing an interactive knowledge base for pine regeneration for the Louisiana Forestry Productivity Program. Louisiana Department of Agriculture and Forestry. Principal Investigator. Co-principal investigators: M. Dunn and M. Chamberlain. $370,303.00. 2001-2006.

Enhancing lidar-based estimates of forest stand structure through incorporation of low-altitude hyperspectral imagery. Remote Sensing Technology Center at Mississippi State University. Coprincipal Investigator, Other investigators: S.D. Roberts and D. Evans (Mississippi State University). $112,350 for two years; subcontract to LSU Ag Ctr $8,400. 2000.

Enhancement of Forestry, Wildlife, and Fisheries education through technology. LSU Student Technology Fee Disciple Specific Grant. Coprincipal Investigator. Other investigators: J.L. Chambers (PI), Q.V. Cao; R. Vlosky. $92,550. 1999

Leaf area and volume estimates in loblolly pine forests derived from aerial imaging LIDAR. NASA. Coprincipal Investigator. $278,961 for two years; subcontract to LSU Ag Ctr $52,430.00. 1999-2001.

Comparative Effects of thinning on residual stand structure and growth. USDA Forest Service Cooperative Agreement. 1997-2000. Principal Investigator. $23,000.00. 1997-2000.

Evaluation of reforestation techniques for converted wetlands in the Lower Mississippi Alluvial Valley. USGS Biological Survey Research Work Order. Principal Investigator. $30,000.00. 1993-1994.

Climate change effects on forest biomass and growth: establishing a baseline using size--density relations. USDA Forest Service Cooperative Agreement. 1992-1995. Principal Investigator. $12,500.00. 1992-1995.

Response of slash pine families to acidic precipitation and ozone stress in North Florida. USDA Forest Service Cooperative Agreement. 1987-1992. Coprincipal Investigator. $1,404,000.00. 1987-1992.

Editorial boards:

2002-present Associate Editor, Silviculture (pine), Southern Journal of Applied Forestry

2002-present Editorial board, Forest Ecology and Management

Publications (underlined names: graduate students, postdoctoral researchers, and employees):

Peer-reviewed

Cao, Q.V. and T.J. Dean. 2008. Using segmented regression to model the density–size relationship in direct-seeded slash pine stands. Forest Ecology and Management *in press.*

Dicus, C.A. and T.J. Dean. 2008. Tree-soil interactions affect production of loblolly and slash pine. Forest Science *in press*.

Scott, D.A. and **T.J. Dean.** 2006. Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations. Biomass and Bioenergy 130:001-1010

Carter, M.C., **T.J. Dean**, Z. Wang, R.A. Newbold, and T. Cooksey. 2006. Impacts of harvesting and post-harvest treatments on soil bulk density, soil strength, and early growth of *Pinus teada* L.: an LTSP affiliated study. Canadian Journal of Forest Research 36: 601-614.

Roberts, S.D., **T.J. Dean**, D.L. Evans, J.W. McCombs, R.L. Harrington, and P.A. Glass. 2005. Estimating individual tree leaf area in loblolly pine plantations using LiDAR-derived measurement of height and crown dimensions. Forest Ecology and Management 213: 54-70.

Jerez, M., **T.J. Dean**, Q.V. Cao, and S.D. Roberts. 2005. Describing leaf area distribution in loblolly pine plantations with the Johnson's S_B function. Forest Science 51: 93-101.

Long, J.N., **T.J. Dean**, and S.D. Roberts. 2004. Linkages between silviculture and ecology: examination of several important conceptual models. Forest Ecology and Management 200: 249-261 .

Sword, M.A., J.C. Goelz, J.L. Chambers, Z., Tang, **T.J. Dean**, J.D. Haywood, and D.J. Leduc. 2004. Long-term trends in loblolly pine productivity and stand characteristics in response to thinning and fertilization in the western Gulf region. Forest Ecology and Management 192:71-96.

Jerez, M., **T.J. Dean**, S.D. Roberts, and D.L. Evans. 2004. Patterns of branch permeability with crown depth among loblolly pine families differing in growth rate and crown size. Trees- Structure and Function 18: 145-150.

Thomas Joseph Dean (continued)

Dean, T.J. 2004. Basal area increment and growth efficiency as functions of canopy dynamics and stem geometry. Forest Science 50: 106-116.

Roberts, S.D., **T.J. Dean**, and D.L. Evans. 2003. Family influences on leaf area estimates derived from crown and tree dimensions in *Pinus taeda*. Forest Ecology and Management 172: 261-270.

Dean, T.J. and Q.V. Cao. 2003. Inherent correlations between stand variables calculated from tree measurements. Forest Science 49: 279-284.

Lockhart, B.R., B. Keeland, J. McCoy, and **T.J. Dean**. 2003. Comparing regeneration techniques for afforesting previously farmed bottomland hardwood sites in the Lower Mississippi alluvial valley, USA. Forestry 76: 169-180.

Carter, M. C., **Dean, T.J.**, Zhou, M., Messina, M. G., Wang, Z. 2002. Short-term changes in soil C, N, and biota following harvesting and regeneration of loblolly pine (*Pinus taeda* L.). Forest Ecology and Management. 164: 67-88.

Dean, T.J. and S.J. Chang. 2002. Using simple marginal analysis and density management diagrams for prescribing density management. Southern Journal of Applied Forestry 26: 85-92.

Dean, T.J, S.D. Roberts, D.W. Gilmore, D.A. Maguire, K.L. O'Hara, R.S. Seymour, and J.N. Long. 2002. An evaluation of the uniform stress hypothesis based on stem taper in select North American conifers. Trees- Structure and Function 16: 559-568.

Dean, T.J. 2001. Potential effect of stand structure on belowground allocation. Forest Science 47: 69-76.

Cao, Q.V., **T.J. Dean,** and V.C. Baldwin, Jr. 2000. Modelling the size--density relationship in direct-seeded slash pine stands. Forest Science 46: 317-321.

Dean, T.J. and V.C. Baldwin, Jr. 1996. The relationship between Reineke's stand-density index and physical stem mechanics. Forest Ecology and Management 81: 25-34.

Dean, T.J. and V.C. Baldwin, Jr. 1996. Growth-growing stock relations in loblolly pine as a function of canopy dynamics. Forest Ecology and Management. Forest Ecology and Management 82: 49-58.

Christopher B. Allen

1014 S. 18th St. Apt. 2
Baton Rouge, LA 70802
(225) 336-9264 (home)
(225) 578-4519 (work)
calle25@lsu.edu

EDUCATION

Master of Science, Forest Ecology, December 2003
D.B. Warnell School of Forest Resources, University of Georgia, Athens, GA
Thesis: The effects of resource availability on canopy dynamics and radiation use efficiency in managed forest stands.
Advisor: Rodney E. Will

Bachelor of Science, Forestry, May 2000
Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA

CURRENT RESEARCH

My current research is in the field of forest ecology and soils. Specifically, I am the coordinator of CRiSSSP (Cooperative Research in Sustainable Silviculture and Soil Productivity) at Louisiana State University. CRiSSSP is a cooperative between Louisiana State University, the USDA Forest Service, Louisiana Tech University, and several forest industries. My research focuses on the effects of forest management practices on vegetation dynamics and soil physical and chemical properties.

AWARDS/AFFILIATIONS

Society of American Foresters, 2000-present
- Chair, Southeastern Louisiana Chapter, 2006

Xi Sigma Pi, National Forest Resources Honors Society, 1999-2003
Phi Sigma, National Biological Honors Society, 1998-2000
Alpha Zeta, National Agricultural Honors Society 1998-2000
Recipient of 2nd place award in the Forest Biology section of the 2003 Graduate Student Symposium, Warnell School of Forest Resources, University of Georgia

STUDY ABROAD

Study abroad program of Virginia Tech, University of Stellenbosch, South Africa, January 1999-December 1999

- Studied South African flora, ecology, forest management, entomology

PROFESSIONAL EXPERIENCE

Research Associate, January 2004 - present
School of Renewable Natural Resources, Louisiana State University

Graduate Research Assistant, August 2001 December 2004
Warnell School of Forest Resources, University of Georgia

Forest Ecology Teaching Assistant, January 2002 May 2002
Warnell School of Forest Resources, University of Georgia

Research Technician, May 2001 – August 2001
Warnell School of Forest Resources, University of Georgia

Land Surveyor, August 2000 May 2001
Anderson and Associates, Inc., Blacksburg, VA

Exotic Species Control/Forest Health Technician (volunteer), May 1998 August 1998
Student Conservation Association, Great Smoky Mountains National Park

PUBLICATIONS

Allen, C.B., Will, R.E., and M.A. Jacobson. 2005. Production efficiency and radiation use efficiency of four tree species receiving irrigation and fertilization. Forest Science 51: 556-569.

Allen, C.B., Will, R.E., McGarvey, R.C., Coyle, D.R., and M.D. Coleman. 2005. Radiation-use efficiency and gas exchange responses to water and nutrient availability in irrigated and fertilized stands of sweetgum and sycamore. Tree Physiology 25:191-200.

Allen, C.B., Will, R.E., Sarigumba, T, Jacobson, M., Daniels, R.F., and S. Kennerly. 2004. Relationship between canopy dynamics and stem volume production of four species receiving irrigation and fertilization. P. 343-347 *in* Proceedings of the 12th Biennial Southern Silviculture Research Conference, K.F. Connor (ed.). Gen. Tech. Rep. SRS-71. USDA Forest Service, Southern Research Station, Asheville, NC.

ORAL PRESENTATIONS

Allen, C.B., Will, R.E., Jacobson, M.A., and R.F. Daniels: "Production efficiency, radiation use efficiency, and canopy dynamics of four tree species receiving irrigation and fertilization." 6th Biennial Meeting of the Short Rotation Woody Crops Operations Working Group, Charleston, SC. November 2004.

Christopher B. Allen (continued)

Allen, C.B.: "The effect of water and nutrient availability on canopy dynamics and radiation conversion of four tree species." Invited presentation, Plum Creek Timber Company, Inc., Watkinsville, GA. December 2003

Allen, C.B., Will, R.E., Coyle, D.R., Coleman, M.D., and R.C. McGarvey: "The effect of resource availability on canopy dynamics and biomass accumulation in fertigated hardwood stands." 88th Annual meeting of the Ecological Society of America, Savannah, GA. August 2003

Allen, C.B., Will, R.E., Sarigumba, T., Jacobson, M.A., Daniels, R.F., and S. Kennerly: "Relationship between canopy dynamics and stem volume production of four species receiving irrigation and fertilization." Graduate Student Symposium, Warnell School of Forest Resources, University of Georgia, Athens, GA. March 2003

Allen, C.B., Will, R.E., Sarigumba, T, Jacobson, M.A., Daniels, R.F., and S. Kennerly: "Relationship between canopy dynamics and stem volume production of four species receiving irrigation and fertilization." 12th Biennial Southern Silviculture Research Conference, Biloxi, MS. February 2003

Will, R.E., **Allen, C.B.** (co-presenter), Daniels, R.F., and R.C. McGarvey: "The effects of water and nutrient availability on the radiation use efficiency and photosynthetic capacity of short rotation woody crops." Short Rotation Woody Crops Cooperative Research Program Annual Meeting, Aiken, SC. October 2002

PRESENTED POSTERS

Allen, C.B. and T.J. Dean. The effect of harvesting practice and site preparation method on mineralizable nitrogen in young loblolly pine stands. 13th Biennial Southern Silviculture Research Conference, Memphis, TN. February 2005.

Allen, C.B., Dean, T.J, and D.A. Scott. Nitrogen mineralization and uptake in young loblolly pine stands as affected by site occupancy . 14th Biennial Southern Silviculture Research Conference, Athens, GA. February 2007.

Melinda Hughes

Melinda Hughes
Senior Research Associate
School of Renewable Natural Resources
Louisiana State University Agricultural Center
Baton Rouge, LA
Work Phone (225) 578-4940; Fax 578-4227

EDUCATION
B.S., Forestry, Louisiana Tech University
M.S., Botany, Louisiana Tech University

EMPLOYMENT AND RESEARCH INTERESTS
As a research associate for the School of Renewable Natural Resources, Melinda served as the coordinator of the project "Managing Louisiana Forests for Water Quality" where she worked closely with local, state, and federal agencies to address forestry and water quality issues within the State. She was instrumental in co-publishing "Managing Louisiana's Forests for Water Quality", an overview of the importance of protecting forested stream habitats and wetland ecosystems.
Currently her research efforts include baldcypress and bottomland hardwood growth responses to environmental stresses, and regeneration of bottomland hardwoods. She was a member of the Governor's Coastal Wetland Forest Conservation and Use Science Working Group.
Other work experiences include: Research Associate at Louisiana Tech University where she coordinated two projects funded by the Louisiana Department of Natural Resources. She also served as a Research Associate for the Hill Farm Research Station and worked for the U.S. Forest Service as a Soil Scientist where she was instrumental in developing and implementing the first, national, long-term forest soil productivity study. Her work experience also includes three years as an Environmental Specialist for Louisiana's Department of Environmental Quality, Office of Water Quality.

PUBLICATIONS

Faulkner, S.P., J.L. Chambers, W.H. Conner, R.F. Keim, J.W. Day, E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer Conservation and Use of Coastal Wetland Forests in Louisiana. 2007. Chapter 16 - in Conner WH, Doyle TW, Krauss KW (eds) Ecology of tidal freshwater swamps of the southeastern United States (Springer Publishers, New York).

Keim, R.F., Chambers, J.L, Hughes, M.S., Dimov, L.D., Conner, W.H.,Shaffer, G.P., Gardiner, E.S., Day, J.W. 2006. Long-Term Success of Stump Sprouts in Cutover High-Graded Baldcypress–Water Tupelo Swamps in the Mississippi Delta. Forest Ecology and Management 234:24-33.

Melinda Hughes (continued)

Keim, R.F., Chambers, J.L. Hughes. M.S.. Gardiner, E.S., Conner. W.H., Day, J.W., Faulkner, S.P., King. S.L.. McCleod, K.W., Miller, C.A., Nyman. J.A.. Shaffer. G.P., Dimov, L.D. 2006. Long-term success of baldcypress stump sprouts. Proceedings of the 13th Biennial Southern Silvicultural Research Conference. Connor, K.F. (ed.). Gen. Tech. Rep. Asheville. NC: USDA Forest Service. Southern Research Station. 559-563.

Chambers, J.L., Conner, W.H., Day, J.W., Faulkner. S.P., Gardiner. E.S., Hughes, M.S., Keim, R.F., King, S.L., McLeod, K.W., Miller, C.A., Nyman, J.A., and Shaffer, G.P. 2005. Conservation, protection and utilization of Louisiana's Coastal Wetland Forests. Final Report to the Governor of Louisiana from the Coastal Wetland Forest Conservation and Use Science Working Group. (special contributions from Aust, W.M., Goyer, R.A., Lenhard, G.J., Souther-Effler, R.F., Rutherford, D.A., and Kelso, W.E.). 121p.

Keim, R.F., J.L. Chambers, M.S. Hughes, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, G.P. Shaffer, and L. Dimov. 2006. Long-term success of stump sprouts in baldcypress. pp. 559-563.Conner, Kristina F. (ed.) Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station..

Keim R.F., J.L. Chambers, M.S. Hughes, J.A. Nyman, C.A. Miller, W.H. Conner, J.W. Day Jr., S.P. Faulkner, E.S. Gardiner, S.L. King, K.W. McLeod, and G.P. Shaffer. 2006. Ecological consequences of changing hydrological conditions in wetland forests of coastal Louisiana. pp. 383-395. In ((ed) Y. Jun Xu. Coastal Environment and Water Quality. Proceedings of 25th American Institute of Hydrology. International Conference on Challenges in Coastal Hydrology and Water Quality. Water Resources Publications. Highlands Range. CO. 519 p.

Chambers, J.L., W.H. Conner, R.F. Keim, S.P. Faulkner, J.W. Day Jr., E.S. Gardiner, M.S. Hughes, S.L. King, K.W. McLeod, C.A. Miller, J.A. Nyman, and G.P. Shaffer, 2006. Towards sustainable management of Louisiana's coastal wetland forest: Problems, constraints, and a new beginning. pp. 150-157. ASABE International Conference on Forest Hydrology and Management of Forest Wetlands. Publisher, American Society of Agricultural Engineers, St. Joseph Michigan.

TOM COUSTE', P.E.
JESCO - SR. PROJECT MANAGER

EDUCATION

McNeese State University, B.S., Civil Engineering, 1998

PROFESSIONAL REGISTRATION

P.E., Louisiana, No. 30614
P.E., Arizona, No. 43290

KEY QUALIFICATIONS

Mr. Cousté serves as the Sr. Project Manager for JESCO Environmental & Geotechnical Services, Inc. (JESCO) on multiple debris monitoring contracts and remediation projects involving the management of office and field personnel. Mr. Cousté has experience designing and implementing site investigations, risk evaluations, construction and demolition activities, Corrective Action Plans, as well as interfacing with State and Federal regulatory agencies to insure compliance with all regulations.

In addition, Mr. Cousté services as the Environmental Engineer on a variety of environmental compliance projects. Mr. Cousté has planned, developed, and obtained 26 Corps of Engineers Section 404 and Section 10 permits, designed and acquired a NPDES Permit for a 30,000 bpd refinery, designed and developed 2 Type III Landfills, modified 2 Type III Landfills, designed 5 Stormwater Pollution Prevention Plans, performed onsite training for client personnel to assume stormwater inspections, completed 18 Phase I environmental site investigations for local industrial and commercial properties, completed 5 Environmental Baseline Studies for the Federal Government, responsible for providing regulatory liaison with USCOE, LDEQ, EPA, etc., developed 12 Needs Analysis and Alternate Sites Analysis studies for Corps of Engineering, and assisted in 15 wetland delineations and determinations.

RELEVANT PROJECT EXPERIENCE

Disaster/Emergency Services

Hurricane Rita, QA Services for Debris Mission, Louisiana Department of Transportation and Development District 07, (Various Louisiana Parishes) – Mr. Cousté served as the Senior Project Manager for JESCO for state projects involving inspection and recordation of debris removal after Hurricane Rita for Louisiana Department of Transportation and Development District 07 regarding the FEMA/USACE debris removal mission. This involved the supervision of various sized groups of personnel working in locations that were devastated from hurricane Rita (Calcasieu, Cameron, Jeff Davis, Allen, Beauregard Parishes).

Mr. Cousté supervised quality assurance inspectors in measuring and documenting demolition and debris quantities associated with the above-described project as well as all construction and demolition estimates associated with project remediation activities. Mr. Cousté developed and administered various programs that include debris inspector and team leader training. Mr. Cousté attended update meetings for the State and Local officials.

Hurricane Rita, QA Services for Debris/Vegetation Mission,* Calcasieu Parish Police Jury, *(Calcasieu Parish) – Mr. Cousté served as the Senior Project Manager for JESCO for the parish project involving inspection and recordation of trimming of dangerous vegetation in Calcasieu Parish roadway right-of-ways after Hurricane Rita for FEMA/USACE debris removal mission. This involved the supervision of various sized groups of personnel working in locations that were devastated from hurricane Rita (Calcasieu Parish roadways). Mr. Cousté supervised quality assurance inspectors in eligible trimming determination, which included branch trimming, tree removal, and stump removals. Mr. Cousté conducted update meetings for the Local officials. Mr. Cousté developed and administered various programs that include debris inspector and team leader training.

Hurricane Rita, QA Services for Debris Mission, City of Lake Charles, (Lake Charles, LA) – Mr. Cousté served as a supervisor for JESCO for city projects involving inspection and recordation of debris removal after Hurricane Rita for the City of Lake Charles Public Works Division. Mr. Cousté supervised quality assurance inspectors in measuring and documenting demolition and debris quantities associated with the above-described project. Mr. Cousté supervised the measuring of trucks and trailers.

Hurricane Katrina, Emergency Services and Debris Clearing, Federal Reserve Bank – New Orleans Branch, (New Orleans, LA) – Mr. Cousté served as the project manager for JESCO for Federal Reserve Bank projects involving emergency services and debris clearing support after Hurricane Katrina. Mr. Cousté coordinated the timely procurement and delivery of potable water, bulk fuel, and food by JESCO transportation crews. Additionally, Mr. Cousté provided coordination and supervision of emergency debris and refuse removal services for the New Orleans Branch.

Site Assessment/ Risk Evaluation/ Environmental Remediation

Washington Citgo, (Washington, LA) – Mr. Cousté serves as the project manager/engineer for a 9-city block hydrocarbon release at Washington Citgo. Mr. Cousté oversaw all site assessment activities (18 borings, 10 monitoring wells – 60 feet deep), prepared the site assessment report, and reviewed the Risk Evaluation. Mr. Cousté designed and implemented an interim corrective action due to the large amount of LNAPL located on the groundwater. Mr. Cousté developed a pilot study to analyze the true radius of influence and actual recovery rates. Currently, Mr. Cousté is designing the Corrective Action report for the facility. Also, Mr. Cousté reviews the quarterly monitoring well data and develops the semi-annual reports.

City of Breaux Bridge Water Plant, (Breaux Bridge, LA) – Mr. Cousté serves as the project manager for multiple hydrocarbon releases at the Breaux Bridge Water Plant. Mr. Cousté prepared the Corrective Action report for the facility. Additionally he designed two (2) dual phase extraction remediation systems to be installed at the facility. The treatment systems are designed with a recovery rate of between 12,800,462 – 17,379,490 gallons per year for two years. Currently, he is overseeing the unit construction phase.

Auzeune & Dessalle, (Opelousas, LA) – Mr. Cousté serves as the project engineer for JESCO for the Auzeune & Dessalle Site. He oversaw all site assessment activities (23 borings, 22 monitoring/recovery wells), prepared the site assessment report, prepared the Risk Evaluation, and Corrective Action report for the facility. He designed a dual phase extraction remediation systems to be installed at the facility. The treatment system will consist of a fifty (50) horsepower oil cooled liquid ring pump, 80 gallon centrifugal vapor/liquid separator, fifteen gpm oil/water separator, fifteen (15) gpm tray type counter current air stripper, associated transfer pumps, instrumentation and a central control panel. The units will remediate soil and groundwater. Mr. Cousté reviews the quarterly monitoring well data and develops the semi-annual reports.

Louisiana Department of Transportation and Development – Indian Inn Station, (Pollock, LA) – Mr. Cousté serves as the project engineer for JESCO for the Indian Inn Site. He oversaw all site assessment activities (10 borings, 5 monitoring/recovery wells, P&A of 2 damaged wells), prepared the additional site assessment report, and compared the assessment data to the original Risk Evaluation. Mr. Cousté reviews the quarterly monitoring well data and develops the semi-annual reports.

<u>Construction</u>

LA Hwy. 165 UST Project, (Oakdale, LA) – Mr. Cousté served as the project manager for JESCO for the LA Hwy. 165 UST project. He oversaw all UST closure activities (removal of 29 USTs with dispenser islands), environmental sampling, and prepared the closure reports. Mr. Cousté planned and supervised the removal of contaminated soils at various UST locations. Mr. Cousté also planned and supervised the remedial excavation closure samples. Mr. Cousté reviewed the closure data and developed additional closure reports.

<u>Environmental Compliance</u>

Union Pacific Storage-In-Transit Railcar Yard, (Sulphur, LA) – Mr. Cousté served as the environmental engineer for the 1,300 railcar Union Pacific SIT yard project. Mr. Cousté developed a need analysis plan and alternate sites analysis plan for the 256-acre facility, worked with the local planning and zoning board to rezone the area to be developed, assisted in obtaining the Section 404 Permit, and developed the Stormwater Pollution Prevention Plan for the construction phase. Mr. Cousté provided weekly inspections of the stormwater structures and erosion control measures.

Chaney Trucking Landfill, (Leesville, LA) – Mr. Cousté served as the environmental engineer for the Chaney Trucking Landfill. Mr. Cousté developed and obtained the Type III Landfill application, collected geotechnical samples, re-zoned the developed, obtained the water quality permits, developed the Stormwater Pollution Prevention Plan, and provided the initial inspection of the project.

TRAINING

- 29 CFR 1910.120 Hazardous Waste Operations and Emergency Response HAZWOPER (40 HR)
- 8 hr. Manager/Supervisors Training Course in 29 CFR 1910.120 and DOT HM-12F Hazardous Operations and Emergency Response

PROFESSIONAL AFFILIATIONS

- National Society of Professional Engineers,
- Louisiana Engineering Society,
- The Society of American Military Engineers, and
- Army Engineering Association

INDEFINITE DELIVERY CONTRACT W912P8-07-D-0040
TASK ORDER NO. 0002

I. GENERAL DATA

SUBJECT: Tree Root Documentation and Analyses in support of Corps of Engineers Tree Removal Program at Levees and Floodwalls in New Orleans District

FIRM: JESCO

CONTRACT NUMBER:

PROJECT LOCATION: The project area is broadly defined as the 1,300 miles of Corps of Engineers levees in the New Orleans District located in southern Louisiana. The study area for data collection will be focused on tree removal project areas in the metropolitan New Orleans area including, but not limited to: East Jefferson lakefront levee, the New Orleans lakefront levee, Orleans Avenue Canal levee/floodwall on City Park side, both sides of the London Avenue Canal, and both sides of the 17th Street Canal.

II. **PERFORMANCE BASED WORK STATEMENT**

The New Orleans District, U.S. Army Corps of Engineers (MVN) requires data gathering and analyses of tree root extent and behavior to support the refinement of vegetation management guidelines for Federal and non-Federal levees and floodwalls. The contractor will conduct comprehensive literature review and consultations with local and regional experts to develop baseline information on tree root behavior. The contractor will also investigate the feasibility and effectiveness of remote sensing techniques for determining root extent in local soil conditions. The scope of the research will include tree root barrier products to determine various types available, costs and effectiveness. The documentation and analyses of tree root extent and behavior will take advantage of data available during the uprooting and/or removal of trees and stumps from various levee and floodwall reaches in MVN as part of the on-going tree removal program. The contractor will gather data on root sizes, vertical and horizontal extent, soil characteristics, root behavior adjacent to levees, and tree performance during high winds and other storm events. The data will be collected and analyzed by tree species, tree size or age, soil types, and other defining parameters. Comprehensive draft and final reports will be prepared.

Corps of Engineers guidance contained in Engineer Manual 1110-2-301 provides for a "vegetation-free zone" of 15 feet at the toe of levee structures and a 3-foot "root-free zone" immediately adjacent to the levee section. Requirements for floodwalls vary. Other Corps documents address vegetation management adjacent to flood control features but generally lack specific distances between trees and structures.

III. DESCRIPTION OF WORK AND SERVICES

The study shall be performed in three phases/tasks as provided below:

- Phase 1 – Literature Review and Consultation with Experts
- Phase 2 – Data Gathering
- Phase 3 – Data Analyses and Report Preparation

The table below provides performance metrics for each of the tasks to be performed.

Performance Objective	Performance Threshold	Method of Surveillance	Outcome for Failure
Literature Review and Consultation with Experts	Contractor performs thorough review and consultations to confirm fieldwork methodology.	The Contractor will present preliminary (phase 1) report to the Project Delivery Team. Delivery is monitored by PM.	Payment will be withheld until the preliminary report is accepted by PM (per Payment Milestone 1 in section VII).
Data Gathering	Completion of all required fieldwork, office research, and tree removal monitoring.	The conduct of fieldwork will be monitored by PM and PDT.	Failure to complete all fieldwork and other data gathering will result in withheld payment (per Payment Milestone 2 in section VII).
Data Analyses and Report Preparation	Completion of all technical analyses and report meeting the requirements of the scope of work.	The technical studies documentation will go through PDT review and approval. Delivery is monitored by PM.	Payment will be withheld until the Comprehensive Report is accepted by the PM (per Payment Milestone 3 in section VII).

IV. DETAILS OF THE WORK TASKS

Study Objective: The objective of the tree root study is to identify and quantify, where possible, tree root behavior in the vicinity of flood control structures and features. The results of the study will provide information required to support the development of effective, specific and empirically-based vegetation management guidance for MVN projects.

Phase 1. Literature Review and Consultation with Experts

The contractor will begin with a comprehensive literature review and consultations with local and regional experts to develop baseline information on tree root behavior. The literature to be reviewed includes professional journals and publications as well as student theses and other sources. Emphasis will be placed upon regional publications, in particular those specific to Louisiana trees and soil characteristics. An area of focus during the research will be root behavior under compacted soils, such as under levees, roads and other man-made features. In addition, the Contractor will consult national, regional and/or local tree experts (arborists, landscape architects, urban foresters, etc.) to compile available knowledge on tree root behavior and performance during storm events.

The scope of the research will include remote sensing technologies that might be used to delineate tree root extent and characteristics. The effectiveness of such methods in local soil conditions will be evaluated. In addition, the contractor will investigate tree root barrier products to determine various types available, costs and effectiveness. The Contractor will review available literature on root barriers utilized to identify the different types and manufacturers available in the marketplace. The contractor will evaluate the effectiveness of the various barriers in blocking undesirable root penetration and any problems or limitations in their use. The relative costs of implementation and maintenance of root barriers will also be evaluated.

Phase 2: Data Gathering

While the phase 1 efforts are underway, the contractor will initiate documentation and analyses of tree root extent and behavior, taking advantage of data available during the uprooting and/or removal of trees and stumps from various levee and floodwall reaches in MVN as part of the on-going tree removal program. The contractor will gather data on root sizes, vertical and horizontal extent, soil characteristics, root behavior adjacent to levees, and tree performance during high winds and other storm events.

The Contractor will work closely with the Government's project manager to schedule fieldwork to gather information as separate tree removal contractors are performing their work. The contractor will exercise caution to avoid interference with the tree removal contractor's work efforts while gathering the required data. The stump removal contractor will remove stumps by pulling them up or pushing them over and all roots larger than 0.5 inches in diameter will be removed by excavation and individual pick-up removal. Stump grinding will not be utilized except in special circumstances approved by the Government. Root removal is only to occur within the levee section and available right-of-way, which is usually a 6 foot zone adjacent to the levee toe area.

The contractor will also excavate several inspection trenches to identify, document and remove roots from large trees outside of the work area, e.g. beyond 6 feet from the levee toe. Tree roots identified during the trenching operations will be measured and traced out towards the levee until diameter size is 0.5 inches or smaller. All identified roots larger than 0.5 inches will be removed. Since the work will be conducted in the vicinity of heavy equipment, all appropriate safety precautions will be followed.

In addition to data gathered in Government stump/root removal areas (East Jefferson lakefront levee, the New Orleans lakefront levee, Orleans Avenue Canal levee/floodwall on City Park side, both sides of the London Avenue Canal, and both sides of the 17th Street Canal), the Contractor will supplement the data gathering with data available from uprooted trees obtained from other sources and locations in the New Orleans metropolitan area. This might include tree removal by FEMA or by private parties.

Phase 3: Data Analyses and Report Preparation

The data will be collected and analyzed by tree species, tree size or age, soil types, and other defining parameters. Contractor will determine tree root spread and depth of various tree types. Drawings, graphics and presentation boards will be developed for report illustration and use in public meetings. Root analysis will be determined based upon various tree trunk sizes measured at diameter breast high (DBH). An analysis determining effect of overturned trees will be included. Size of root ball, anticipated hole/depression resulting from overturned tree will also be analyzed. Diagrams will be presented in the report graphically depicting the results. Trees shall be analyzed within various ground condition scenarios including dry ground, wet conditions, compacted soil etc. Varied root growth conditions (depth, spread, and size) will be studied and documented in the report for typical tree types found in southern Louisiana along levees and floodwalls. The analyses and report will also address remaining data gaps and further research needs.

V. SUBMITTALS AND PERIOD OF PERFORMANCE

Deliverables

Several written reports are required under this task order. These reports include a preliminary report for the phase 1 tasks, and comprehensive draft and final reports for phases 1 through 3.

a. Preliminary Report (Phase 1 tasks). Four copies of a brief report summarizing the results of Phase 1 shall be submitted within 4 weeks after award of the task order and notice to proceed (NTP). This interim report will present data developed during review of the literature and consultation with experts. The report text will be accompanied by data tables and graphical representations, as appropriate. The Project Manager will provide comments on the preliminary report within two weeks of submittal.

b. Comprehensive Study Report (Phases 1-3). Four copies of the draft report integrating the results of all the required tasks for Phases 1, 2, and 3 will be submitted for review and comment within 12 weeks after award and NTP of the task order. This comprehensive draft report will provide a complete presentation of the results of the research and data gathering phases. The report text will be accompanied by data tables and graphical representations. The Government will provide all review comments to the contractor within 4 weeks after receipt of the draft reports. Upon receipt of the review comments on the draft report, the contractor shall incorporate or resolve all comments and submit a preliminary final copy of the report within 2 weeks (18 weeks after task order award). Upon approval of the preliminary final report (within 1 week after submittal), the contractor will submit 20 bound copies and one unbound copy of the final report within 20 weeks after task order award.

VI. SCHEDULE

The contractor is required to commence work within 10 calendar days of the award of this Task Order and NTP. The schedule of deliverables for this task order is summarized below:

	Deliverable	Due (after NTP)
a.	Preliminary Report (Phase 1)	4 weeks
b.	Draft Comprehensive Report	12 weeks
c.	Prelim. Final Comprehensive Report	18 weeks
d.	Final Comprehensive Report	20 weeks

VII. MILESTONES AND PAYMENTS

a. **Milestone 1** – The CONTRACTOR shall complete Task 1 and submit the preliminary report within 4 weeks of award of the task order and NTP in order to receive 25% of the total contract payment.

b. **Milestone 2** – The CONTRACTOR shall complete Tasks 1-3 and submit an acceptable draft comprehensive report in order to receive 50% of the total contract payments.

c. Milestone 3 – Upon acceptance of the final comprehensive reports and computer files, the CONTRACTOR will receive the final 25% of the total contract payments.

VIII. GUIDANCE

The Contractor is cautioned to disregard guidance pertaining to the interpretation of specific requirements of the contract or modifications to the contract, during the course of the study, from any source other than the Contracting Officer's Representative (COR).

IX. PROJECT MANAGEMENT

Mr. Lamar Hale is the COR and primary point-of-contact (POC). The Corps project manager for technical questions and coordination regarding the specific tasks of this contract is Mr. Stephen F. Finnegan. All deliverable items shall be delivered to the following address:

Mr. Stephen F. Finnegan
ATTN: CEMVN-PRO
U.S. Army Corps of Engineers, New Orleans District
P.O. Box 60267
New Orleans, Louisiana 70160-0267
Phone: (504) 862-2553

The Corps of Engineers project manager may visit the A-E Contractor to review or inspect the progress of the work or to resolve questions concerning the development of work covered under this Scope-of-Work, at any time after giving notice.

X. PUBLICITY AND RELEASE OF DATA

Except with prior approval from the Government, the contractor, including any of his employees or consultants, shall not release for publication or any other use (including student theses or professional journals) any sketch, photograph, report, or other material of any nature pertaining to any matters for which services are performed under the terms of this contract. The provisions of this article shall extend also to the release of any such material to any person, including the public media and the professional community, not so authorized by the Government.

XI. COMPUTER FILES

Computer files of all final deliverables will be provided in IBM Windows-based software formats along with the final reports. The Contractor will provide computer disk(s) of the text of the final reports in Microsoft Word for Windows format. If the Contractor produces written reports in a page layout program, the file format required is Adobe PageMaker. Database files will be provided in .dbf format; spreadsheet files will be provided in Microsoft Excel .xls format; presentation files in Microsoft

PowerPoint format; and CAD files will be provided in Intergraph, .dgn format. In addition to the data files described above (but not in lieu of said files), the contractor may also submit fully integrated files (text and images/charts in a single un-editable document) in Adobe Acrobat (.pdf format).

Each diskette will be clearly labeled with the following information at a minimum: report title, report number, contractors' name, file names, and format. The contractor shall also supply a complete listing of all computer files submitted. This listing will include file names, file types (software and version), disk number, and file description.