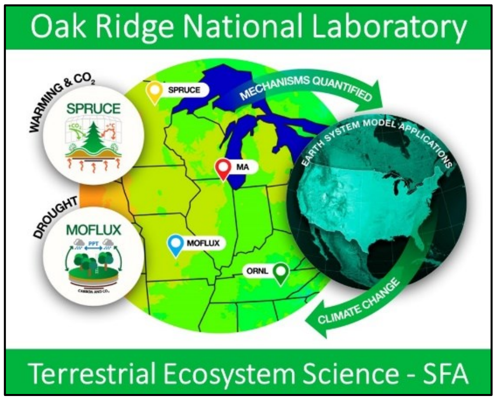
January 24, 2025

TARP: Identifying Critical Thresholds for Acute Response of Plants and Ecosystems to Water Stress at Walker Branch Watershed, 2002-2005



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1. Data Set Overview:

This dataset contains data from a manipulative field study aimed at identifying critical thresholds for acute response of plants and ecosystems to water stress (TARP) that took place at Walker Branch Watershed in Oak Ridge, Tennessee from 2002-2005 (2002-06-20 to 2005-12-16). The study used understory tents for the removal of 100% of the growing-season throughfall and stem flow, to provide data on the impact of acute drought on mechanisms responsible for growth and mortality of deciduous forest canopy trees representative of common plant functional types (Liriodendron and Quercus). Through three years of manipulation (2003, 2004 and 2005; pretreatment measurements in 2002) various measures of tree response to surface moisture deficits were recorded including root and leaf traits, plant nonstructural carbohydrates status, hourly sapflow, basal area, and periodic observations of foliar photosynthesis and conductance. Additionally, environmental data such as air and soil temperature, soil water content, and soil matric potential were recorded. This dataset contains 16 files in comma-separate (*.csv) format.

Related Publication:

The measurements and results of this study have been described in the following publication:

Hanson PJ, TJ Tschaplinski, SD Wullschleger, DE Todd Jr., and RM Augé. 2007. The resilience of upland-oak forest canopy trees to chronic and acute precipitation manipulations. [In: Buckley DS and Clatterbuck WK, (Eds.)], Proceedings 15th Central Hardwood Forest Conference, Knoxville, TN February 27–March 1, 2006, e-General Technical Report SRS–101, United States Department of Agriculture, Forest Service Southern Research Station, pp. 3-12.

Data Citation:

Cite this data set as follows:

Hanson PJ, RM Augé, TJ Tschaplinski, SD Wullschleger, DE Todd and TA Ruggles. 2025. TARP Identifying Critical Thresholds for Acute Response of Plants and Ecosystems to Water Stress at Walker Branch Watershed, 2002-2005. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/ornlsfa.026/1853796

Related Data Sets

Hanson PJ, Todd DE, Riggs JS, Wolfe ME, O'Neill EG. 2001. Walker Branch Throughfall Displacement Experiment Data Report: Site characterization, system performance, weather, species composition and growth. ORNL/CDIAC-134, NDP-078A. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. 158 p. https://doi.org/10.2172/814151

2. Data Characteristics:

Spatial Coverage

The TARP experiment was conducted at an upper ridge line above Walker Branch watershed in Oak Ridge, TN. The following coordinates are the central location of the *Quercus prinus* and *Liriodendron tulipifera*.

Site boundaries: Latitude and longitude given in decimal degrees.

Site	Longitude	Latitude	Elevation (meters amsl)
Q. prinus tree cluster	-84.2798	35.9676	362-374
L. tulipifera tree cluster	-84.2905	35.9609	357

Temporal Coverage

2002-06-20 to 2005-12-16

Measurement increments vary from hourly for environmental data to annual.

Data File Description

These data are considered at **Quality Level 1**. Level 1 indicates an internally consistent data product that has been subjected to quality checks and data management procedures.

Missing numeric data are indicated by -9999. Missing text values are indicated by N/A.

This dataset contains 16 files in comma-separate (*.csv) format:

- *Table01_TARP_Environmental_Data_2003_2005.csv:* Contains environmental data including air and soil temperature, relative humidity, incident light, wind speed, and vapor pressure.
- *Table02_TARP_Horizontal_Soil_Water_2003_2005.csv*: Contains horizonal soil water content and soil matric potential measurements.
- *Table03_TARP_Vertical_Soil_Water_2003_2005.csv*: Contains vertical soil water content and soil matric potential measurements.
- *Table04_TARP_Heat_Dissapation_SWP_2003_2005 csv*: Contains soil matric potential measurements and heat dissipation data.
- *Table05_TARP_Basal_Area_2022.csv*: Contains growth in basal area measures from 2022 at approximately weekly intervals.
- *Table06_TARP_Basal_Area_2003_2005.csv*: Contains basal area measures and basal area cumulative growth for each tree from 2003 to 2005. Measurements were taken at approximately weekly intervals.
- *Table07_TARP_Multiyear_BAI.csv*: Contains basal area, basal area index, and diameter at breast height data.
- *Table08_TARP_LAI_2003_2004.csv*: Contains leaf traits including leaf mass per unit are and leaf area index.
- *Table09_TARP_Gravimetric_Roots_by_Depth: Contains _2003.csv*: Contains root mass measurements.
- *Table10_TARP_Root_Counts_By_Depth.csv*: Contains root count measurements collected in fall 2005.
- *Table11_TARP_Root_Penetration_at_1_4m.csv*: Contains root characteristics collected in fall 2005 from the root penetration study.
- *Table12_TARP_Foliar_Physiology_Means.csv*: Contains foliar philological traits.
- *Table13_TARP_TNC_Values_2002_2005.csv*: Contains tree tissue sugar, starch, total nonstructural carbohydrate (TNC) concentrations.
- *Table14_TARP_Sapflow.csv*: Contains relative sapflow velocities
- *Table15_TARP_Axial_Root_Cond.csv*: Contains root axial conductance measurements.
- *Table16_TARP_Root_Radial_Cond.csv*: Contains root radial conductance measurements.

Data Dictionary for *Table01_TARP_Environmental_Data_2003_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	YYYY	Year of observation
MOY	MM	Month of year
DOY	DDD	Day of year
DFOY	N/A	Day fraction of year
HOY	N/A	Hour of year
Quan	umol m-2 s-1	Incident Light – Quantum
Pyran	W m-2	Incident Light - Pyranometer
QuanUnder	umol m-2 s-1	Understory Light - Quantum

TA	Degrees C	Air temperature
RH	Percent	Relative humidity
PPT	mm h-1	Cumulative precipitation over one hour
Wind	m s-1	Mean wind above the canopy
TST15	Degrees C	Mean soil temperature
Sat_VP	kPa	Saturated vapor pressure for TA
Obs_VP	kPa	Observed vapor pressure for TA = (VP_Sat * RH/100)
VPD	kPa	Vapor pressure deficit (VP_Sat -VP_Obs)

Data Dictionary for *Table02_TARP_Horizontal_Soil_Water_2003_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation
Date	YYYY-MM-DD	Time of litter collection
DOY	DDD	Day of the year
RDOY	DDD	Days since 1 January 2003
Tree_Num	N/A	Sequential number of study trees randomly assigned to treatments
SPC	N/A	Species. Liriodendron tulipifera (Lt) or Quercus prinus (Qp)
TREAT	N/A	Treatment. Ambient controls (Amb) or Precipitation exclusion (Dry)
HLOC	N/A	Compass direction with each plot for a pair of TDR rods approximately 5 m from the tree trunk.
SWC_035	percent (v/v)	Soil water content from 0 to 035 cm.
SWC_070	percent (v/v)	Soil water content from 0 to -70 cm
SWC_3570	percent (v/v)	Soil water content from -35 to -70 cm. Calculated deep soil water content per the approach of Hanson et al. 2003
SWP_035	MPa	Soil matric potential calculated from SWC data for 0 to -35 cm
SWP_3570	MPa	Soil matric potential calculated from SWC data for -35 to -70 cm

Data Dictionary for *Table03_TARP_Vertical_Soil_Water_2003_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation
Date	YYYY-MM-DD	Time of litter collection
DOY	N/A	Day of the year
RDOY	N/A	Days since 1 January 2003
TreeNum	N/A	Sequential number of study trees randomly assigned to treatments
SPC	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)

TREAT	N/A	Treatment. Ambient controls (Amb) or Precipitation exclusion (Dry)
TDR_Depth	cm	Soil depth for buried probe SWC determination
Depth_Horizon	N/A	Soil horizon designation
Measured_SWC	percent (v/v)	TDR assessment of soil water content
Buried_A_Hoizon_SMP	Mpa	Soil matric potential calculated from A horizon SWC
Buried_E_Horizon_SMP	MPa	Soil matric potential calculated from E horizon SWC
Buried_B_Horizon_SMP	MPa	Soil matric potential calculated from B horizon SWC data

Data Dictionary for *Table04_TARP_Heat_Dissapation_SWP_2003_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
YEAR	N/A	Year of observation
RDOY	DDD	Days since 1 January 2003
DOY	DDD	Sequential day of year
HOD	N/A	Sequential hour of year
DFOY	N/A	Fractional day of year
Species	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)
DRY_HD_4_5_cm	Delta degrees C	Depth specific measured heat dissipation
DRY_HD_12_22_cm	Delta degrees C	Depth specific measured heat dissipation
DRY_HD_27_32_cm	Delta degrees C	Depth specific measured heat dissipation
DRY_HD_47_57_cm	Delta degrees C	Depth specific measured heat dissipation
DRY_SMP_4_5	MPa	Soil matric potential for noted depth
DRY_SMP_12_22	MPa	Soil matric potential for noted depth
DRY_SMP_27_32	MPa	Soil matric potential for noted depth
DRY_SMP_47_57	MPa	Soil matric potential for noted depth
AMB_HD_4_6	Delta degrees C	Depth specific measured heat dissipation
AMB_HD_16_22	Delta degrees C	Depth specific measured heat dissipation
AMB_HD_27_36	Delta degrees C	Depth specific measured heat dissipation
AMB_HD_46_51	Delta degrees C	Depth specific measured heat dissipation
AMB_SMP_4_6	MPa	Soil matric potential for noted depth
AMB_SMP_16_22	MPa	Soil matric potential for noted depth
AMB_SMP_27_36	MPa	Soil matric potential for noted depth
AMB_SMP_46_51	MPa	Soil matric potential for noted depth

Data Dictionary for *Table05_TARP_Basal_Area_2022.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of growing season observations.
Date	YYYY-MM-DD	Date of dendrometer band measurement.
DOY	DDD	Day of year beginning on 1 January of each year.
Mid_Date	N/A	Day of the year halfway between sequential dendrometer band observations.
Species	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)

Tree_Num	N/A	Sequential tree numbers randomly assigned to treatments.
Treat	N/A	Treatment. Ambient controls (Amb) or Precipitation exclusion (Dry)
BA_Per_Day_mm	mm2 d-1	Average basal area growth per day between two sequential dendrometer band measures. Calculation is based off the dendrometer band measurement on listed date and the previous measurement. Calculations assume a circular basal area for all trees.

Data Dictionary for *Table06_TARP_Basal_Area_2003_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	YYYY	Year of growing season observations. 2002 is only a partial year.
Date	YYY-MM-DD	Sample date
DOY	DDD	Day of year beginning on 1 January of each year.
Species	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)
TreeNum	N/A	Sequential tree numbers randomly assigned to treatments.
Treat	N/A	Ambient controls (Amb) or Precipitation exclusion (Dry)
Circum_cm	cm	Tree circumference at DBH from the dendrometer band measurement
BA_cm	cm	Basal area calculated from the dendrometer band measurement.
Delta_BA_cm	cm	Growth in basal area at DBH between two sequential dendrometer band measures. Calculations assume a circular basal area for all trees.
BA_Per_Day_mm	mm2 d-1	Average basal area growth per day between two sequential dendrometer band measures. Calculation is based off the dendrometer band measurement on listed date and the previous measurement. Calculations assume a circular basal area for all trees.
Cumulative_BA_mm	mm	Cumulative growth in basal area for a given year.

Data Dictionary for *Table07_TARP_Multiyear_BAI.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation
Species	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)
Treatment	N/A	Treatment. Ambient controls (Amb), Precipitation exclusion (Dry), or pretreatment (PRE)
Tree_Num	N/A	Sequential tree numbers randomly assigned to treatments.
Init_DBH	cm	Initial DBH in cm
Init_BA	cm2	Initial basal area in cm2.
BAI_cm	cm2 y-1	Annual increment of basal area in cm2
BAI_mm	mm2 y-1	Annual increment of basal area in mm2

Data Dictionary for *Table08_TARP_LAI_2003_2004.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation. Litter was collected in 2003, 2004 and 2005, but the 2005 values have been lost.
Date	YYYY-MM_DD	Time of litter collection
SPC	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)
Tree_Num	N/A	Sequential tree numbers randomly assigned to treatments.
Treat	N/A	Treament. Ambient controls (Amb) or Precipitation exclusion (Dry)
Rep_1	g	grams leaf litter per basket
Rep_2	g	grams leaf litter per basket
Mean	g	Mean leaf litter per basket
Leaf_Mass	g	Cumulative leaf litter mass for all sampling dates within a year.
LMA	g m-2	Measured leaf mass per unit area (LMA) for the determination of LAI.
LAI	m2 m-2	Mass//0.2014 m2 per basket/LMA

Data Dictionary for *Table09_TARP_Gravimetric_Roots_by_Depth_2003.csv*

Column Name	Units	Description
Species	N/A	Speices. Liriodendron tulipifera (Lt) or Quercus prinus (Qp)
TreeNum	N/A	Number of the measured tree that was randomly assigned to treatment plots. Trees 1 to 8 are Qp. Trees 9 to 16 are Lt.
Depth	cm	Depth increment for cylindrical sampling core.
Core_Num	N/A	Replicate core in the footprint of the sampled tree.
Raw_Mass	g	Dry root mass plus bag
Tare	g	Bag mass
Root_Mass	g	Final dry root mass
Notes	N/A	Notes

Data Dictionary for *Table10_TARP_Root_Counts_By_Depth.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Species	N/A	Species. Liriodendron tulipifera (Lt) Quercus prinus (Qp)
Tree_Num	N/A	Number of the measured tree that was randomly assigned to treatment plots. Trees 1 to 8 are Qp. Trees 9 to 16 are Lt.
Treat	N/A	Treament. Ambient controls (Amb) or Precipitation exclusion (Dry)

Depth	cm	Depth of the bottom of a layer used to count roots. 10 cm increments
DepthMid	cm	Midpoint depth for the soil layer being evaluated.
Distance	m	Distance along the excavated trench for the evaluation panel.
S2mm	count	Summed count of roots in the layer that were < 2mm in diameter
S2to5mm	count	Summed count of roots in the layer that were between 2 and 5 mm in diameter
S5mm	count	Summed count of roots in the layer that were > 5mm in diameter

Data Dictionary for *Table11_TARP_Root_Penetration_at_1_4m.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Species	N/A	Species. Liriodendron tulipifera (Lt) or Quercus prinus (Qp)
TreeNum	N/A	Number of the measured tree that was randomly assigned to treatment plots. Trees 1 to 8 are Qp. Trees 9 to 16 are Lt.
Treat	N/A	Treament. Ambient controls (Amb) or Precipitation exclusion (Dry)
X	cm	Distance in cm from tree
Y	cm	Distance in cm across the trench
Diameter	mm	Diameter of penetrating root
M2	m2	Root cross section area in m2

Data Dictionary for *Table12_TARP_Foliar_Physiology_Means.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation
Date	DDD	Day of the year
Species	N/A	Liriodendron tulipifera (Lt) Quercus prinus (Qp)
Treat	N/A	Ambient controls (Amb) or Precipitation exclusion (Dry)
CER	umol m-2 s-1	Foliar net photosynthetic rate at high light and prevailing [CO2]
CER_stat	N/A	Significance of Foliar net photosynthetic rate at p=0.05. The same letters within a date are nonsignificant treatments.
Cond	mmol m-2 s-1	Foliar Conductance
Cond_Stat	N/A	Significance of Foliar Conductance at p=0.05. The same letters within a date are nonsignificant treatments.
Transp	mmol m-2 s-1	Transpiration
Transp_stat	N/A	Significance of Transpiration at p=0.05. The same letters within a date are nonsignificant treatments.
WP_Leaf	MPa	Leaf Water Potential

WP_stat	N/A	Significance of Leaf Water Potential at p=0.05. The same letters within a date are nonsignificant treatments.
OP_leaf	MPa	Leaf Osmotic Potential at full turgor
OP_stat	N/A	Significance of Foliar Conductance at p=0.05. The same letters within a date are nonsignificant treatments.
OP100_Leaf	MPa	Osmotic potential of leaf at full turgor
OP100_stat	N/A	Significance of Leaf Osmotic Potential at p=0.05. The same letters within a date are nonsignificant treatments.
TP_leaf	MPa	Leaf Turgor Pressure
TP_stat	N/A	Significance of Leaf Turgor Pressure at p=0.05. The same letters within a date are nonsignificant treatments.

Data Dictionary for *Table13_TARP_TNC_Values_2002_2005.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	N/A	Year of observation
Date	YYYY-MM-DD	Sample date
Species	N/A	Liriodendron tulipifera (Lt) Quercus prinus (Qp)
Treat	N/A	Ambient controls (Amb) or Precipitation exclusion (Dry)
Assay	percent	Percent sugar (%Sugar), Percent starch (%Starch), Percent total nonstructural carbohydrate (TNC; sugar + starch), TNCF (TNC g/ (gdry mass-TNC))
Roots	percent	Fine Root Tissues (g/g*100)
Root_SD	percent	Standard deviation of observations (g Assay/g dry mass*100)
Branch	percent	Terminal branch tissue (g Assay/g dry mass*100)
Branch_SD	percent	Standard deviation of observations (g Assay/g dry mass*100)
Stem	percent	Tree bole sapwood tissue(g Assay/g dry mass*100)
Stem_SD	percent	Standard deviation of observations (g Assay/g dry mass*100)

Data Dictionary for Table14_TARP_Sapflow.csv

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Year	YYYY	Year of observation
DOY	DDD	Day of the year
RDOY	DDD	Days since 1 January 2003
Qp_Amb	N/A	Relative sapflow velocity in Quercus prinus ambient treatment. Max per day. 0 to 1 relative scale.
Qp_Dry	N/A	Relative sapflow velocity in Quercus prinus dry treatment. Max per day. 0 to 1 relative scale.
Lt_Amb	N/A	Relative sapflow velocity in Liriodendron tulipifera ambient treatment. Max per day. 0 to 1 relative scale.
Lt_Dry	N/A	Relative sapflow velocity in Liriodendron tulipifera dry treatment. Max per day. 0 to 1 relative scale.

Data Dictionary for *Table15_TARP_Axial_Root_Cond.csv*

Column Name	Units	Description
Species	N/A	Speuces. Liriodendron tulipifera (Lt) or Quercus prinus (Qp).
Depth	N/A	Depth. 15 to 30 cm depth or >90 cm depth
ks_mean	g H2O s-1 mm-2 MPa-1	Axial conductance through roots
ks_stdev	g H2O s-1 mm-2 MPa-1	Standard deviation of axial conductance through roots
n	N/A	Number of assayed samples

Data Dictionary for *Table16_TARP_Root_Radial_Cond.csv*

Column Name	Units	Description
Order	N/A	Order of data with time used to sort the file.
Species	N/A	Species. Liriodendron tulipifera (Lt) or Quercus prinus (Qp)
Tree_Num	N/A	Number of the measured tree that was randomly assigned to treatment plots. Trees 1 to 8 are Qp. Trees 9 to 16 are Lt.
Depth	N/A	Depth from which the root sample was collected.
Lgth	mm	Length of the root sample evaluated
Diam	mm	Diameter of the root sample evaluated
Pres	bar	Pressure applied in bars. 1, 2.5, 5, 7.5 or 10 bars
Flow5	g Solution 5min-1	Flow over 5 minutes
Pressure	MPa	Pressure applied in MPa. 0.1, 0.25, 0.5. 0.75 or 1 MPa
Flow	g Solution s-1	Measured mass flow of root solution per second.
CrossSec	g s-1 mm-2 MPa-1	Conductivity per unit pressure divided by cross sectional area of root
SurfaceArea	N/A	Conductivity per unit pressure divided by root external surface area

3 Applications and Derivation

Changes in regional precipitation expected to result from increasing global temperatures are predicted to have a major effect on the composition, structure and productivity of forest ecosystems (Houghton et al. 2001). Such predicted changes raise concerns about terrestrial ecosystem productivity, biogeochemical cycling, and the availability of water resources (Kirschbaum and Fischlin 1996; Melillo el al. 1990, and the IPCC Working Group II Third Assessment Report (McCarthy et al. 2001) requested further research on the response of ecosystems to multiple stresses (e.g., increased temperature and drought). Unfortunately, the direction and magnitude of expected changes in precipitation remain highly uncertain (Houghton et al. 2001). Given this uncertainty, manipulative field experiments can play a powerful role in the identification of gradual and threshold ecosystem responses that might result from future precipitation changes.

4. Quality Assessment:

These data are considered at **Quality Level 1**. Level 1 indicates an internally consistent data product that has been subjected to quality checks and data management procedures. Established calibration procedures were followed.

5. Data Acquisition Materials and Methods:

Study Site

The experiments were located on the Walker Branch Watershed (35˚58’ N and 84°17’ W), a part of the U.S. Department of Energy’s (DOE’s) National Environmental Research Park near Oak Ridge, Tennessee (Johnson and Van Hook, 1989). Long-term (50-year) mean annual precipitation was 1352 mm and mean annual temperature was 14.2 ºC. The soils are primarily Typic Paleudults derived from dolomitic bedrock. Plant extractable water (water held between 0 and -2.5 MPa) for the upper meter of soil is approximately 183 mm. A large fraction of this water (44 percent) is held in the upper 0.35 m of the soil profile, which is the location of 60 percent of all fine roots in the 0-0.90 m soil profile (Joslin and Wolfe 1998). The soils are highly weathered and very deep (> 10m) on ridge tops and therefore retain little evidence of their carbonate parent material. Deep rooting may be a source of some water. Early aerial photographs show that the study area was forested in the late 1930’s, but several large dominant trees show open growth characteristics suggesting some harvesting before that time. The forest on Walker Branch Watershed is a centrally located example of the eastern broadleaf forest province as defined by Bailey (1983) and historically has been characterized as a *Quercus*/*Carya* forest. Insect outbreaks in the early 1980s, however, decimated the *Carya* populations (Dale et al.1990), and the current forests are better termed upland oak forests.

Quercus spp. and *Acer* spp. are the major canopy dominants across all slope positions. *Liriodendron tulipifera* L. is a canopy dominant on the lower slope positions, and *Acer rubrum* L., *Nyssa sylvatica* Marsh. and *Oxydendrum arboreum* [L.] DC are the predominant species occupying mid-canopy locations. In March of 1994, stand basal area averaged 21.1 m^2 ha^{-1} (Hanson el al. 2001). By April 2004, the mean basal area across all plots had increased to 25.4 m^2 ha^{-1} (Table 1). The number of saplings (trees < 0.1 m dbh) across the study area averaged 3079 trees ha^{-1} in 1994 falling to 1881 ha^{-1} in April of 2005. Saplings contributed an additional 3, 2.6, and 2.5 m^2 ha^{-1} to total stand basal area in 1994, 1999, and 2005, respectively (Table 1). In 1994, *Acer rubrum* L. and *Cornus florida* L. made up 59 percent of all saplings and 53 percent of the sapling basal area (Hanson el al. 2001).

Table 1. Experimental tree characteristics in 2002.

Date Identified	Species	Tree Number	DBH (cm)	Sapwood Thickness (cm)	Starting Dendrometer Measure (mm)	Randomized Treatment Assignment
23-May-02	Qp	1	61.0	4.1	8.25	Dry
23-May-02	Qp	2	54.8	6	18.9	Amb
23-May-02	Qp	3	45.8	3.2	20.18	Amb
23-May-02	Qp	4	63.7	4.3	20.09	Dry
23-May-02	Qp	5	61.8	3.2	18.55	Dry
23-May-02	Qp	6	61.8	4.7	10.96	Dry
23-May-02	Qp	7	56.5	3.7	22.4	Amb
23-May-02	Qp	8	63.8	4.5	10.99	Amb
4-Jun-02	Lt	9	53.9	9.2	12.47	Dry
4-Jun-02	Lt	10	51.4	6.9	9.65	Amb
4-Jun-02	Lt	11	52.1	8.8	21.13	Dry
4-Jun-02	Lt	12	50.3	7.4	18.31	Amb
4-Jun-02	Lt	13	45.8	9.1	18.97	Dry
4-Jun-02	Lt	14	43.2	7.6	19.3	Amb
4-Jun-02	Lt	15	46.8	6.1	19.92	Dry
4-Jun-02	Lt	16	44.1	5	19.44	Amb

Methods

Acute rainfall exclusion methods and modifications

Results of a Walker Branch throughfall displacement experiment (Hanson el al. 2001) showed greater than expected resilience of tree growth in response to chronic drought, the TARP study was conceived to quantify responses to acute and severe soil water deficits. The 'TARP' study used understory tents for the removal of 100 percent of the growing-season throughfall including stem flow from large, individual canopy trees (Figure 1). Sixteen trees for two species of distinct plant functional types *L. tulipifera* (yellow-poplar) and *Q. prinus* (chestnut oak) were measured under ambient and acute drought (DRY) conditions (n = 4 for each species treatment combination).

Each tarped tent area needed to impose the DRY treatment plots covered an area with a minimum circular radius of 10 meters from the target tree bole. The tarped tent area included ten 10x30 foot framed, valanced canopies (Cover Me Tarps and Canopies, Pickens, SC) for throughfall interception, and custom tent with collar to go around the tree stem (Fig 1). All tents were suspended 2 m above the ground to allow for surface air flow and uninterrupted evaporation. Water collection gutters (a custom shaped canvas suspended between framed tents to channel throughfall away from the plot area completed the tented area. Stem flow diverting channels were also added to each tree to collect and divert that component of throughfall precipitation. Collected stem flow (Fig 2a) and the throughfall drainage from the tent-gutter assembly (Fig 2b) were all diverted off each DRY treatment plot via a collection of hoses.

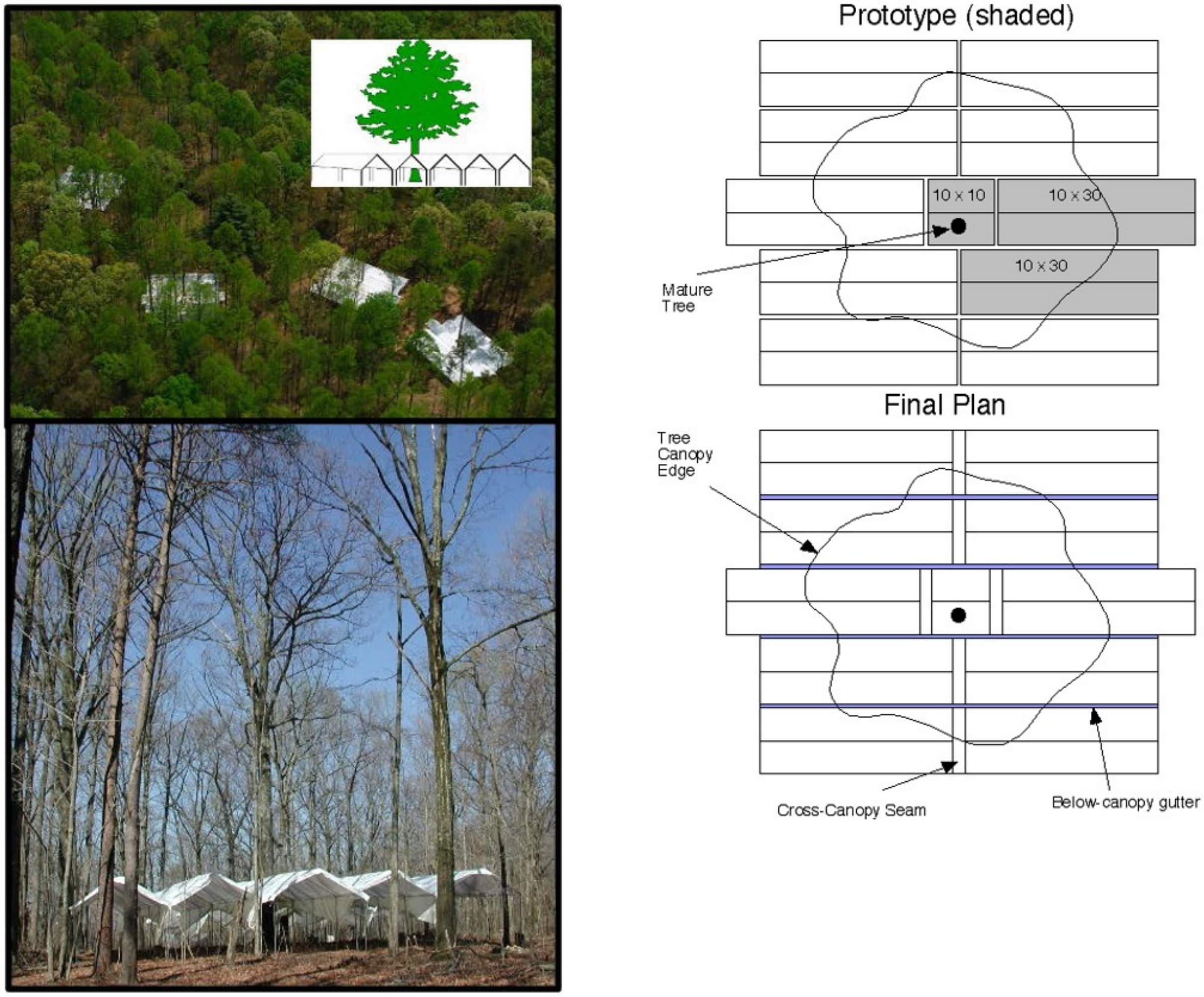

Figure 1. Photograph of a single understory tent area for 100 percent removal of throughfall passing the forest canopy and schematic diagrams of the full roof deployed under a mature canopy tree. The understory roof will be made with custom modifications to commercially available tarp supports (Cover Me Tarps & Canopies, Pickens, SC).

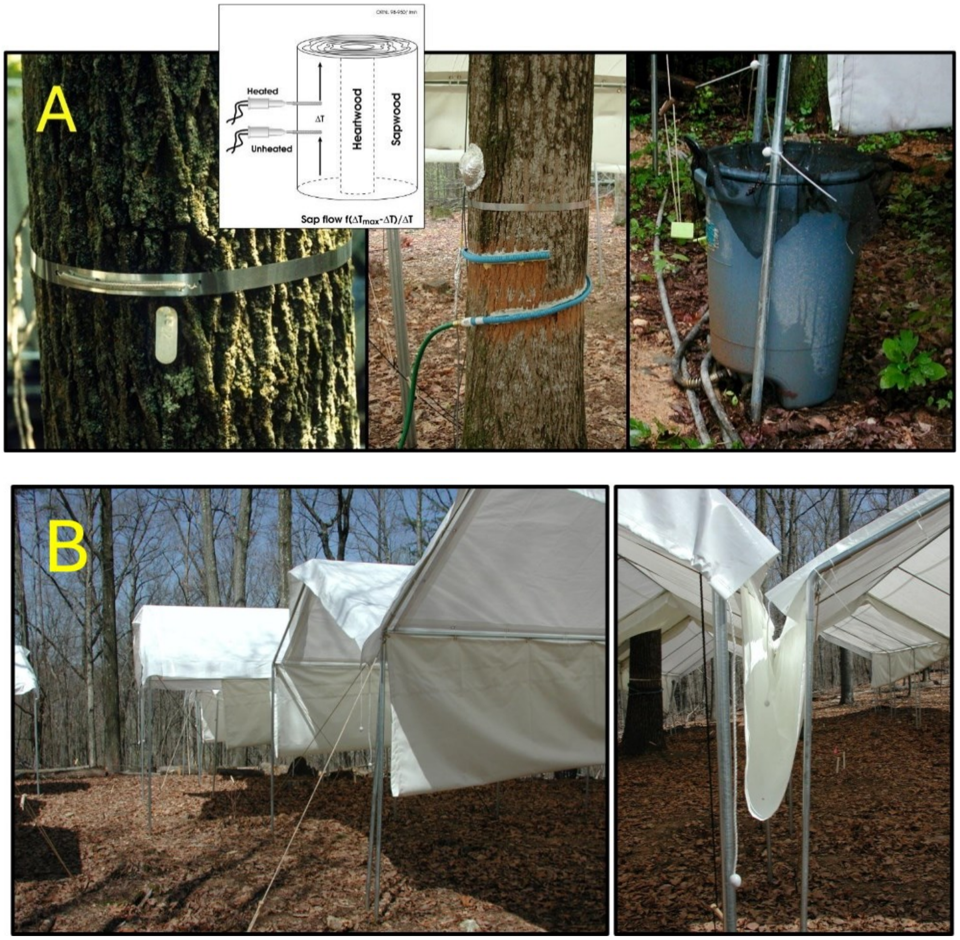

Figure 2. A) An individual tree dendrometer bands, sapflow installations under the insulating foil, stem flow collection collar, and gutter collection canisters that drain away from the Dry treatment plots in a collection of hoses. B) Photographs of the canvas gutter suspended between throughfall interception tents.

The tarped treatment plots and all environmental and soil water monitoring equipment were installed before leaf-out in March of 2003 and were left in place through the 2005 growing season. The ambient plot areas were sized similarly to the DRY plots. All tarped trees and ambient trees had an understory experimental area that exceeded the projected canopy spread for the largest trees.

Trenching of the TARP plots was not done initially to avoid the artifacts of root severing and to allow external tree roots to continue to extract water from the target dry plots. In July of 2004 (following limited tree response to the acute treatments) the TARP treatment plots were trenched with a ditcher to a depth of 50 to 60 cm and width of 20 cm to eliminate potential lateral root water sources. This process severed 100 percent of the lateral roots over this depth representing more than 80 percent of the total know root population at this site (Joslin and Wolfe, 1998).

Environmental data

Regional environmental conditions were measured 0.5km from the TARP study areas (Hanson et al. 1998; 2001) at approximately 35.966, -84.280. Measured variables included air temperature, relative humidity, and soil temperatures (0.1 and 0.35 m) were logged hourly (Campbell Scientific CR10X logger) on each treatment plot. Precipitation, solar irradiance (Pyranometer sensor, LiCor Inc., Lincoln, NE) and photosynthetic photon flux density (Quantum sensor, LiCor Inc.) were also measured continuously and logged as hourly means for one above-canopy location in the vicinity of both experiments.

Soil Water Content and Soil Matric Potential

Soil water content (percent, v/v) was measured with a time domain reflectometer (TDR; TRASE System, Soil Moisture Equipment Corp., Santa Barbara, California) following the procedure of Topp and Davis (1985) as documented for soils with high coarse fraction content (Drungil el al. 1987). Each experimental tree was instrumented with four TDR locations within the canopy drip line. Each of these TDR measurement sites consisted of two pairs of TDR waveguides installed in a vertical orientation (0-0.35 and 0-0.7 m). The surface (0-0.35 m) TDR measurements coincide with the zone of maximum root density in these soils. TDR measurements were obtained periodically during physiological campaigns for the TARP study.

The TDR soil water content measurements were adjusted for the coarse fraction of these soils (mean coarse fraction of 14 percent) and converted to soil matric potentials using laboratory derived soil moisture retention curves for the A, A/E and E/B horizons (Hanson et al. 2003a). To facilitate comparisons of the severity of soil water deficits between years, the minimum soil matric potential (MPa) and calculate a water stress integral (units of MPa d; Hanson et al. 2003a) were measured or estimated for all years and treatments.

Automated hourly observations of soil matric potential were also logged for each TARP tree using heat-dissipation probes (CS229 Heat dissipation matric water potential sensor; Campbell Scientific, Logan, Utah) installed in vertical profiles for each TARP tree (Fig. 3). The depths were 4-5 cm , 12 -22 cm, 27-36 cm, and 46 -57 cm. Raw output from the heat dissipation probes was converted to soil matric potential using the following equation:

(0.0209*1.20501^(HDP^2.40546))*-1

Where HDP is the probe normalized delta temperature output from the heat dissipation probe. This relationship was derived from in situ calibration against periodically measured buriable TDR waveguides (TRASE System probe; Soil Moisture Equipment Corp., Santa Barbara, California) co-located with the heat dissipation sensors.

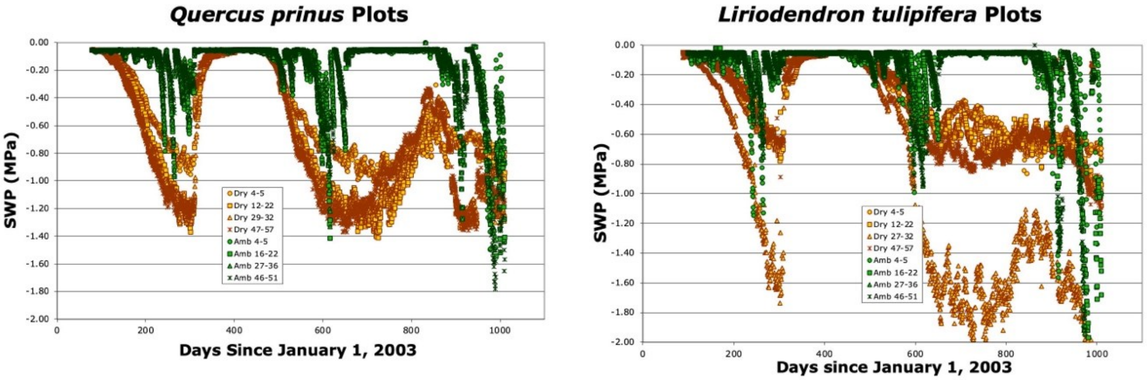

Figure 3. Heat dissipation probe measured soil matric potentials at 4 depths for the ambient (green symbols) and dry (brown symbols) throughout the study period (2003 through 2005).

System Performance

The TARP treatment system was designed to exclude 100% of ambient precipitation over an area extending to (or beyond) the drip line of the individual canopy trees (~310 m2 per tree). Eight independent 'treatment-tarps' were installed and became operational for 4 *Quercus prinus* and 4 *Liriodendron tulipifera* trees on 31 March 2003 prior to canopy leaf out. Eight additional control trees (4 *Q. prinus* and 4 *L. tulipifera* trees) were also instrumented. The experimental treatment plots were not trenched in 2003 to avoid artifacts that might result from root removal, and to allow roots from adjacent trees to extract soil water from beneath the tents. During the winter of 2003/2004 water displacement gutters were removed to allow 'normal' resaturation of the soil profile, but they were replaced prior to leaf out in March 2004.

In 2003, significant drying of soils to a depth of 35 cm was observed as early as day 150 for both species, and both species showed water contents in the surface 10 cm to reach ~5% (v/v) by the end of the growing season (day 288). At 10 to 35 cm the dry treatment soils under *Q. prinus* attained lower soil water contents than *L. tulipifera* by day 288. The pattern was the opposite for the 35 to 55 cm depths where soils were the driest for *L. tulipifera*. Dry plot soil matric potentials showed a continuous decline throughout the growing season reaching depth-averaged minimums around –1.0 and-1.5 MPa for *L. tulipifera* and *Q. prinus*, respectively. A sharp boundary between drought conditions under the tent versus ambient conditions away from the tents was also observed (data not shown). In 2004, lack of early summer rain events led to a faster rate of soil drying, but minimum dry-plot soil matric potentials were similar to those attained in 2003. The depth-specific patterns of soil drying reported for 2003 were also observed in 2004. During the 2004-2005 overwintering soils rewetted to a degree within the Dry *Q. prinus* plots for all depths, but only for the 27 to 32 cm depth for *L. tulipifera.* In both cases SWP remained at midsummer drought levels throughout the winter in contrast to the winter of 2003-2004 when throughfall was allowed to fall in the sub tent space to refill soil water storage reserves.

Growing-season rainfall was sufficient to keep ambient plot soils near field capacity throughout most of 2003 and 2004, but periods of no precipitation in 2005 did allow some drying of the soils of the ambient plots. During mid-summer periods in all years, ambient soils showed transient drying at all soil depths. The late-season transient drying throughout the soil profile in the presence of abundant rainfall inputs suggests that available soil water storage pools for these large trees were indeed being drawn down.

Soil water data contrasting the water use by *Q. prinus* and *L. tulipifera* trees showed that *L. tulipifera* extracted water from deep soil layers earlier in the year than did the *Q. prinus* consistent with the observations of Gale and Grigal (1987). Air temperature and relative humidity at 1 m above the soil surface under the treatment tents did not differ from the ambient plots, but soil temperatures at ~10 cm were 2-3 °C warmer under the tents during the middle of the growing season. Later in the year when the solar angle was reduced these differences were minimized. It is important to recognize that the *Q. prinus* canopies were larger than canopies of *L. tulipifera* with greater LAI. This difference may have reduced total water extraction by *L. tulipifera* trees even though their leaves had higher conductance under high water supply periods.

Limited growth and physiological responses to the imposed droughts were observed in both 2003 and 2004 (discussed in the following sections) leading researchers to revisit the experimental treatment design. During 2003, local weather conditions yielded the 7th wettest growing season (April-October) and the 2nd wettest April to June period over the last 55 years (1949 to 2003). The April to June period coincides with the period of maximum tree growth, and the above-average rainfall during this period hampered the anticipated influence of drought. These extremely wet conditions and the limited plant response to drought in 2003 caused researchers to reconsider the possibility that lateral roots extending beyond the tents and/or deep roots had a greater role in tree water supply than initially expected even though deep-water use is known (Patric et al. 1965). To test for the influence of lateral rooting beyond the tented perimeter, a trench was dug around all dry-plot trees to a depth of ~50 cm in late July of 2004 to sever roots of the target trees that might be accessing ambient water away from the treatment area. No instantaneous responses in sapflow were observed for any Dry treatment tree after trenching suggesting that lateral rooting water supplies at that distance from the tree trunk were on minimal consequence. Subsequent 2004 sampling of canopy photosynthesis and leaf water potential in mid-August also showed no indication of significant lateral rooting influence. It was concluded that large trees for both species have effective deep rooting beyond the high-root-density A and E horizons. No winter throughfall was allowed to amend the Dry treatment plots in the winter of 2004-2005 to maximize the impact of the acute drought in 2005.

The TARP experimental treatments were able to reproduce observed drought conditions known to drive reduced canopy function and premature leaf senescence on Walker Branch in 1998 (Figure ??). The 1998 drought was responsible for a 50% reduction in canopy assimilation and conductance (Wilson et al. 2000a; Wilson and Hanson 2003). Figure 4 contrasts the measured surface (0-35 cm) and deep (35 to 70 cm) soils water content for Walker Branch in the extreme drought year of 1998 with the patterns measured under the TARP dry-plot trees in 2003 and 2004. For *Q. prinus*, the TARP treatments come close to replicating the surface soil conditions observed in 1998, but the deep soils are not as dry. The *L. tulipifera* plots are not achieving drought levels comparable to 1998.

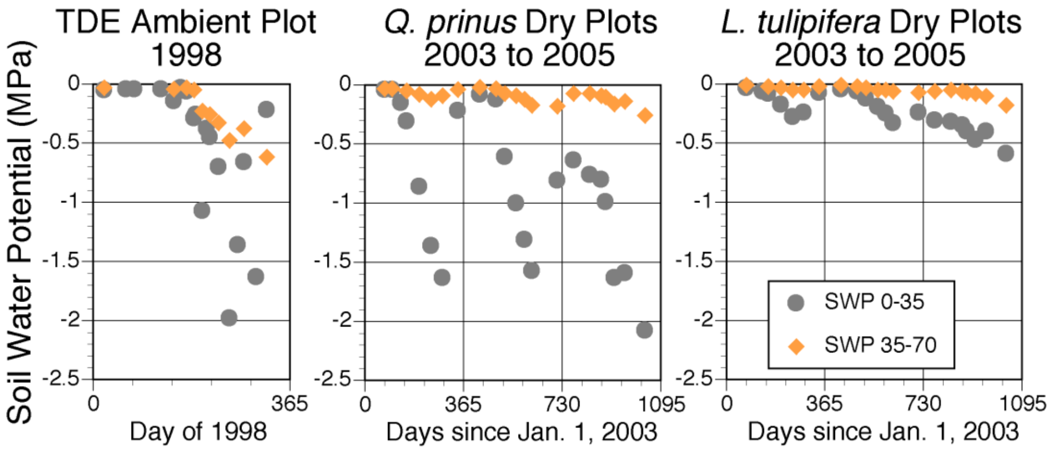

Figure 4. Measured soil matric potentials in surface (0 to 35 cm) and deep (35 to 70 cm) soils for the ambient conditions in 1998 (Hanson et al. 1998 and 2003b) contrasted with the imposed dry plot treatments for Quercus prinus and Liriodendron tulipifera in this study.

Tree Growth Variables

Eight experimental trees of similar size growing at the top of a ridge were chose for this study in late May and early June of 2002 (Table 1). These trees were randomly assigned to the ambient control (Amb) or acute drought (Dry) treatments. The average age for *L. tulipifera* trees ranged from 47 to 64 years, and *Q. prinus* age ranged from 75 to 80 years.

Stem growth – Stem growth measured as changing stem circumference was evaluated by manual dendrometer bands (Fig. 5) installed at the beginning of 2022. The dendrometer bands were measured approximately every two weeks from 23 May through 30 October 2002 before the treatments began, and from February-March through October in 2003, 2004 and 2005. Measured changes in the circumference of each tree were combined with information on its initial stem diameter to obtain the change in stem basal area over time (cm^2 year^{-1}). All dendrometer bands were installed or reset during the dormant season ahead of the initial growth measurements to eliminate potential first year bias in the dendrometer band measurements (Keeland and Sharitz 1993). Shrink/swell patterns capable of being measured by dendrometer bands are smaller than the seasonal change, and were not evaluated.

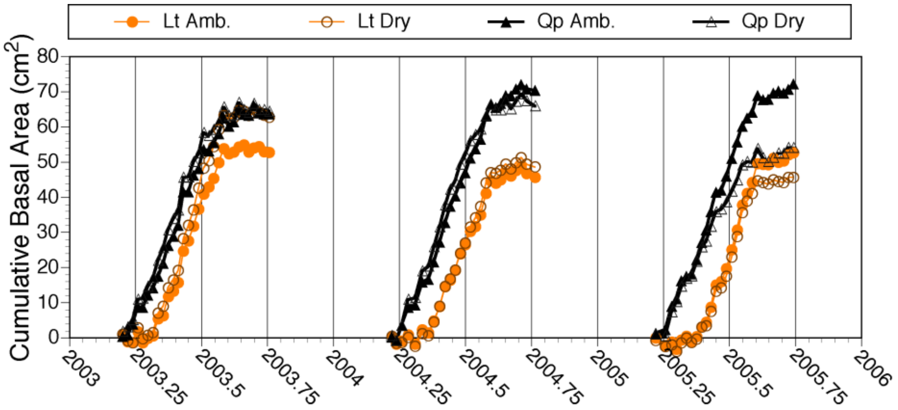

Figure 5. Tree basal area at DBH over the course of the study.

Roots – A traditional rooting depth profile was obtained from traditional coring methods in December 2003, but it did not reach below 0.6 m (Fig.6). Therefore, to better characterize root distributions with depth, side wall by depth count of roots were made at 1, 5 and 10 meters from the trunk of each tree and from 0 to 1.3 meters of trench depth. In addition, the diameters of all roots penetrating the bottom of the excavated trench (nominally 1.4 m deep) were characterized.

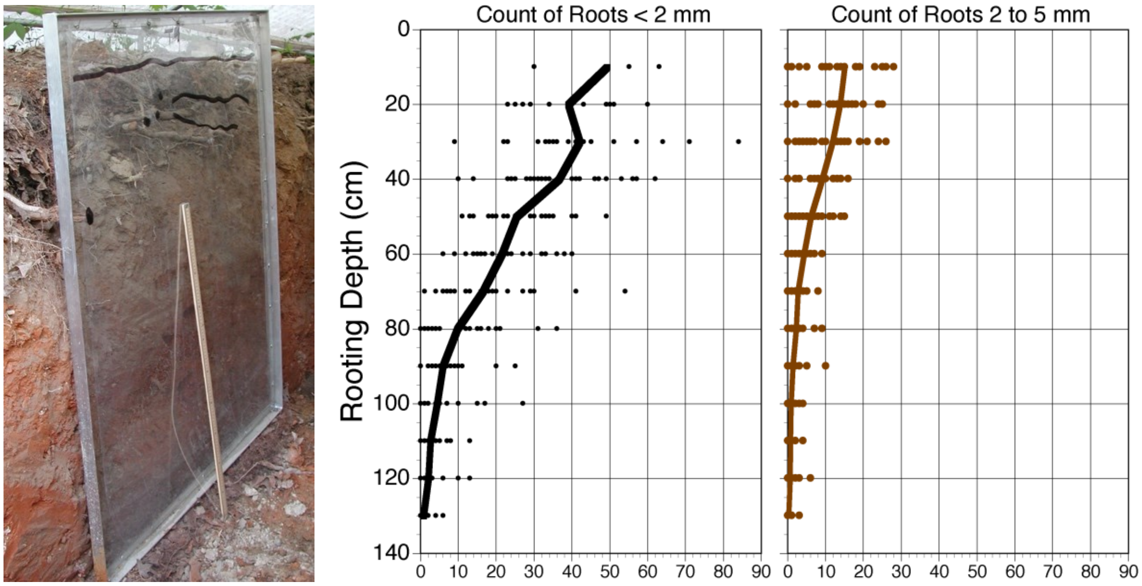

Figure 6. Example of the side wall sample area and marked acetate panel (left = 1 m wide sample “window”) representing one of the panels evaluated at 1, 5 and 10 meters from the trunk of each tree. The right panels show example depth specific mean counts of roots for each panel (heavy lines), counts per trench and depth (individual points), and examples for roots < 2mm and 2 to 5 mm diameter classes.

Leaf Litter and Leaf Area Index – Two replicate litter baskets (readily available plastic laundry baskets with a collection area of 0.2 m^2) were deployed from August through the end of leaf senescence at ground level for Amb treatments or above the throughfall interception tented areas for the Dry treatment trees. **User note:** these data are not currently present in this dataset.

Tree Non-structural Carbohydrate Storage – Nonstructural carbohydrate storage as sugars and starch are a key integrative measure of tree health. This storage reserve is key held over winter is key to the production of new leaves, elongating stems and fine roots prior to the development of canopy leaves in future growing seasons (Gholz and Cropper 1991; Kozlowski et al. 1991). Acute droughts leading to extended periods of reduced photosynthesis and the induction of premature leaf senescence were hypothesized to undermine deciduous plant capacities to regrowth spring leaf, branch and wood. For TARP, measures of nonstructural carbohydrate reserves were collected at various time periods throughout the application of acute drought treatments. Tissue samples were collected multiple times per year: February (dormant season), June (maximum leaf expansion), late summer (just a period of maximum induced drought), and just prior to natural autumn senescence. Terminal branch segments (up to 10 mm diameter), bole (the outer 3 cm of sapwood measured from the bark in), and fine root samples were collected during most time periods. Bole samples were collected from the north side of all trees as a standard practice. All tissues were frozen on dry ice in the field. After field collections the samples were frozen at -80°C, freeze dried, ground and stored at -20°C until analyses could be performed. Total nonstructural carbohydrate assessments were the sum of water-soluble sugars and starch.

Soluble sugars were extracted from 75 mg subsamples of the dried and ground (1 mm pore size) plant material with and 80% aqueous ethanol solution and the residual material containing starch dried (65°C) overnight. The eluant was analyzed for specific and total water-soluble sugars with a gas chromatograph/mass spectrometer using a protocol modified from Tschaplinski et al. (1995). Samples were derivatized with 1 ml acetonitrile and 1 ml MSTFA with 1% TMCS for 30 min at 70°C and a 1µl aliquot used for GCMS runs. Calibrations were done with both internal and external standards.

Starch concentrations of the residual plant materials following sugar extraction were determined using the perchloric acid digestion method of Tissue and Wright (1995).

Few statistically significant treatment differences in TNC or TNC components were observed throughout the entire experimental period. Exceptions include a 12% increase in starch concentration of branches of *Q. prinus* in June of 2003. As a result, TNC content was increased by 9% (Fig 7). The only other treatment difference that approached statistical significance was a 31% increase (p=0.06) in stem starch content of *Q. prinus* sampled in the dormant season after two growing seasons of treatment.

Branch and fine root carbohydrate concentrations within a given species were remarkably stable over time. Bole sapwood carbohydrate content had a more pronounced seasonal dynamic than did other organs. The lowest sugar content in stems was consistently found in September and likely indicates the low carbon allocation priority for sapwood versus branches and fine roots. Typically, the bulk of the TNC storage in the measured organs consisted of starch (data not shown). The extensive amount of carbohydrate data collected to date provides a detailed background against which future treatment differences can be evaluated. The data also suggest that treatment-induced effects on storage carbohydrates that impact growth will most likely be detected in stem sapwood, and those observations will be a priority for future analysis.

Barbaroux et al. (2003) have also confirmed the stem tissues as a low priority sink for TNC, but their data lack the temporal resolution of the TARP observations.

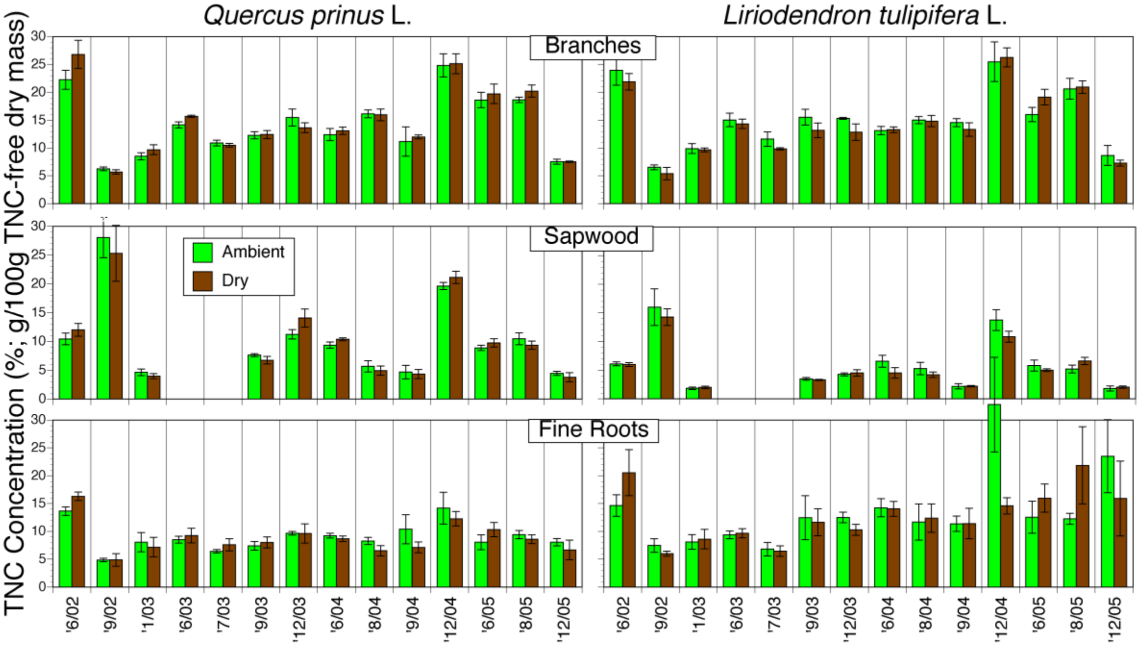

Figure 7. TNC concentrations in branch, sapwood, and fine roots

Tree Physiology Variables

Foliar Net Photosynthesis and Leaf Water Potential – Three time per year (early, middle and late summer) canopy leaves were shot down for the determination of light saturated photosynthesis (CER), leaf conductance (Cond), instantaneous transpiration (Transp), leaf water potential (WP Leaf, pressure chamber), leaf osmotic potential (OP Leaf), leaf osmotic potential at full turgor(OP100), and leaf turgor pressure (TP Leaf). Leaves were sampled from the middle to upper canopies between 0900 and 1600 hours over 1 to 4 days. Sampled leaves were fully expanded near the terminal ends of branches. Four leave per tree were sampled for each measurement a total of 128 measurements per sampling date (4 Leaves, 2 species, 8 trees per species, CER & WP observations).

Assessments of leaf physiological characteristics seldom showed differences in net photosynthetic rates, foliar conductance or leaf water potential variables even though the acute drought had obvious impacts on available soil water (Fig 8.). This provides further evidence that the mature trees of the TARP study growing on deep soils have access to water supplies not typically measured or assessed during drought events.

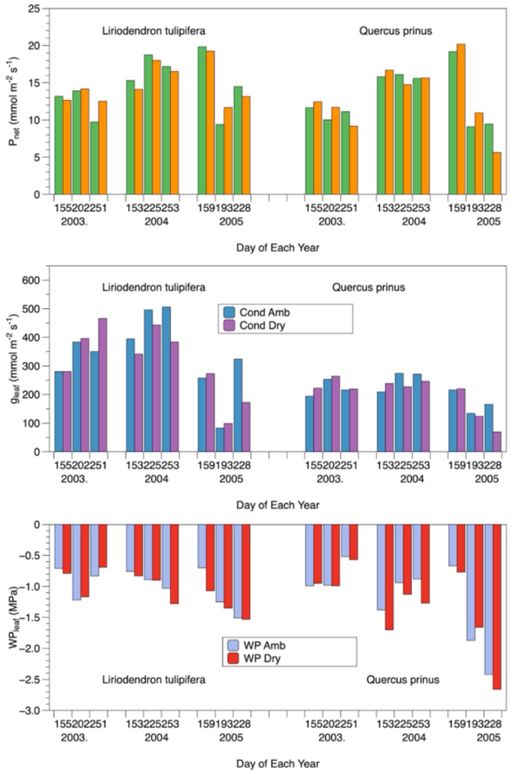

Figure 8. Comparison of net photosynthesis, leaf conductance, and leaf water potential between treatments and species across years.

Sapflow – Hourly rates of sap velocity were measured with thermal dissipation probes *in Q. prinus* and *L. tulipifera* trees from March through October in 2003, 2004 and 2005. Eight trees were measured in each species (i.e., 2 treatments, 4 replicates). Stem diameter (DBH) in 2003 varied from 46.1 to 63.3 cm in *Q. prinus* and 43.2 to 54.0 cm in *L. tulipifera*. Sapwood areas calculated from measured stem diameters and bark and sapwood thicknesses were 601±143 and 847±179 cm^2 in 2003 for *Q. prinus* and *L. tulipifera*, respectively. The values increased slightly in 2004 and 2005. Sapwood thickness as determined by direct measurement with increment cores was greater in diffuse-porous *L. tulipifera* (e.g., 7.3±1.3 cm) than it was in ring-porous *Q. prinus* (e.g., 4.0±0.8 cm).

Seasonal rates of sap velocity measured for both species showed considerable daily variation explained by day-to-day variation in radiation, vapor pressure deficit, and longer-term changes associated with canopy leaf area development and senescence. Hourly rates of sap velocity were typically higher in *L. tulipifera* than they were in *Q. prinus*; 0.075 and 0.071 mm s^{-1} in 2003 and 2004, respectively for *L. tulipifera*, and 0.052 and 0.054 mm s^{-1} in 2003 and 2004, respectively for *Q. prinus*.

Daily rates of whole-tree water use calculated from sap velocity and sapwood area were higher for *L. tulipifera* than for *Q. prinus* (Figure 4). *Q. prinus* trees transpired approximately 80 to 100 kg d^{-1} compared to 120 to 130 kg d^{-1} for *L. tulipifera* trees. Over a 200-day period, rates of whole-tree water use averaged 10,500 kg for *Q. prinus* compared to 14,000 kg for *L. tulipifera*.

Few differences in whole-tree water use were observed between *Q. prinus* trees from either the ambient or dry treatments in 2003, 2004 or 2005 (Fig. 9). In contrast, treatment differences were observed for *L. tulipifera* trees during 2003with late-season (i.e., Jul 25 to Oct 5, 2003) rates of water use 35% lower in the rain-exclusion treatment compared to that of the control trees. Despite similar observed dry treatment soil matric potentials in 2004 and 2005, however, late-season differences in water use for *L. tulipifera* were not observed in 2004 and 2005.

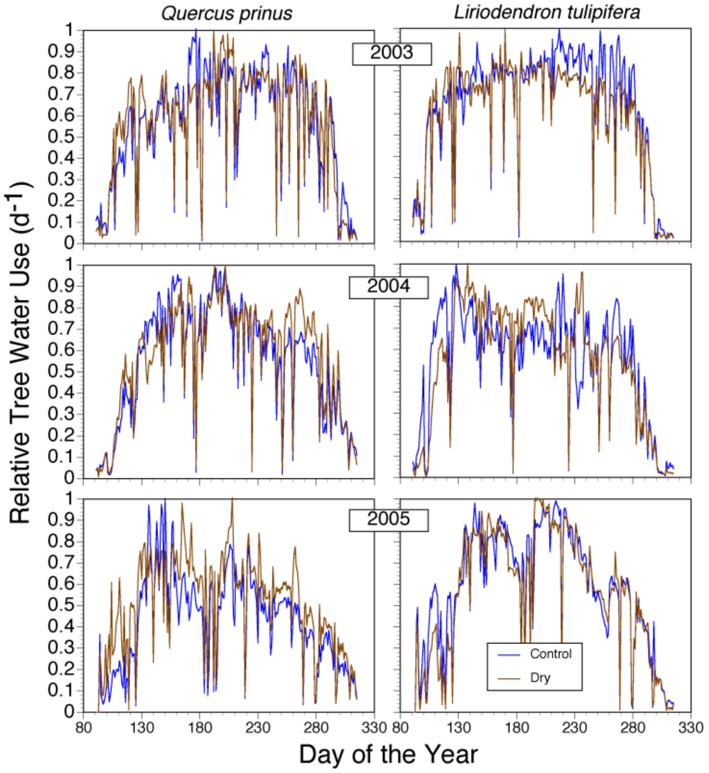

Figure 9. Relative tree water use by species and treatment.

Notwithstanding the limited treatment response of the mature TARP trees in 2003 and 2004, mixed species transpiration responses to years with abundant precipitation vs. extreme drought (Fig. 10) showed a 30% drop in stand water use. Reanalysis of those data for only large *Quercus* trees showed less response to drought consistent with the TARP data. The need for a clear understanding of how large tree, and species-specific water supplies differ within mixed forest stands is suggested by these contrasting results.

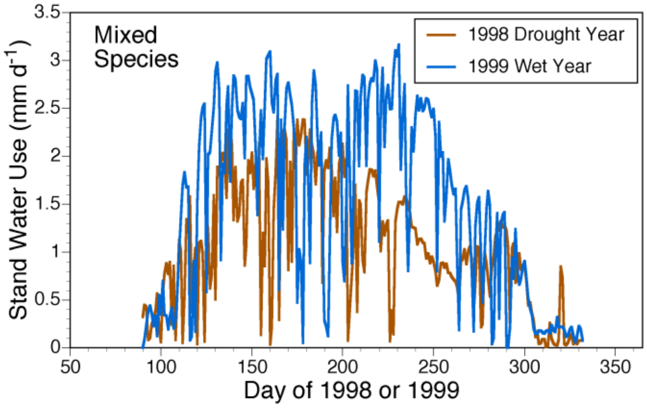

Figure 10. Seasonal patterns of daily water use for a mixed species deciduous forest stand in a drought year (1998 see also Figure 3) and a year with abundant precipitation (1999). These data from the Throughfall Displacement Experiment are for plots adjacent to the locations of the TARP study trees.

Root water axial and radial conductance – To inform models of root water uptake and distribution tissue specific measurements of axial conductance through xylem tissues and radial conductance into roots were evaluated for *Q. prinus* and *L. tulipifera* roots. Roots attached to a water supply for axial conductance and immersed in solution for radial conductance were pressurized by a Scholander pressure vessel (PMS Instrument Company, Corvallis, Oregon) and the exuded root/stem water was collected on a 0.0001g resolution balance and recorded over time. Pressures varied from 1 to 10 bars.

Statistical analyses

The TARP study was conducted on fully replicated mature trees with randomly assigned ambient or dry-plot treatments. One-way analysis of variance with covariates based on initial basal area was used to evaluate significant annual growth responses in the TARP study. Additional regression analyses relating individual tree responses to tree-specific soil water content data are planned for a future paper.

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7. Data Access:

Get Data

For public access to data from the US Department of Energy Terrestrial Ecosystem Science Scientific Focus Ares (TES-SFA) please visit: the TES-SFA website **https://tes-sfa.ornl.gov/node/80** or ESS-DIVE repository (**https://ess-dive.lbl.gov**)

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