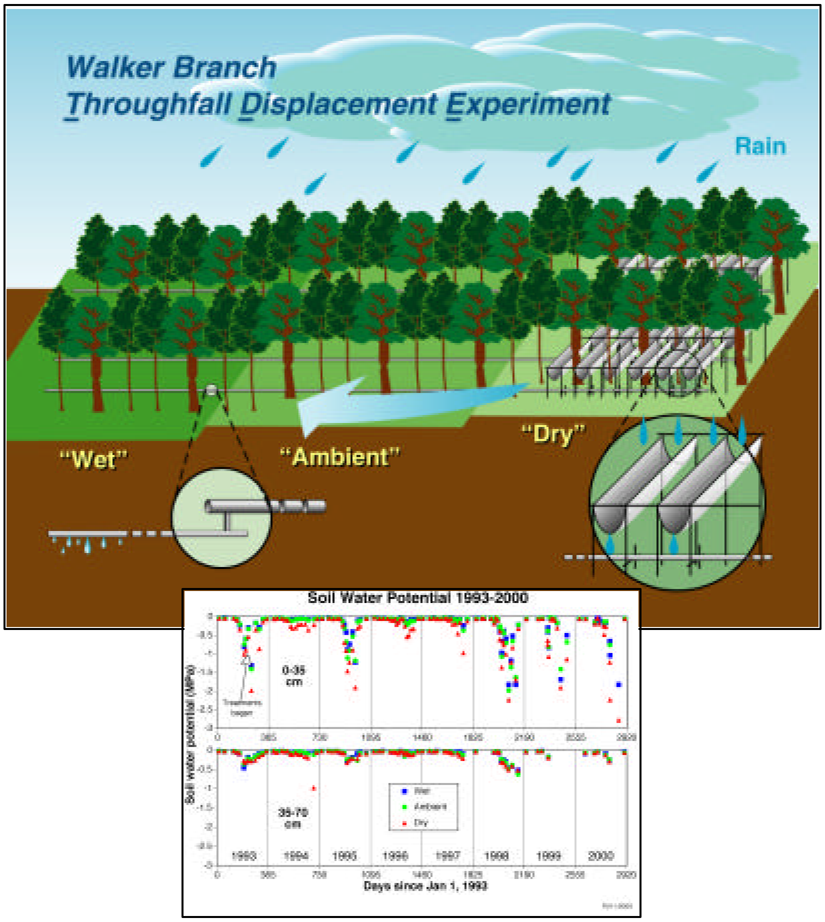
ORNL/CDIAC-134

NDP-078A

Walker Branch Throughfall Displacement Experiment Data Report: Site Characterization, System Performance, Weather, Species Composition, and Growth

Paul J. Hanson
Donald E. Todd
Jeffery S. Riggs
Mark E. Wolfe
Elizabeth G. O'Neill



ORNL/CDIAC-134
NDP-078A

Walker Branch Throughfall Displacement Experiment Data Report: Site Characterization, System Performance, Weather, Species Composition, and Growth

Contributed by

Paul J. Hanson[1]
Donald E. Todd[1]
Jeffery S. Riggs[2]
Mark E. Wolfe[3]
Elizabeth G. O'Neill[1]

[1]Environmental Sciences Division
Oak Ridge National Laboratory

[2]Instrumentation and Controls Division
Oak Ridge National Laboratory

[3]Tennessee Valley Authority
Norris, Tennessee

Prepared by

Robert M. Cushman
Carbon Dioxide Information Analysis Center
Environmental Sciences Division
Oak Ridge National Laboratory

Date Published: July 2001

Prepared for the
Environmental Sciences Division
Office of Biological and Environmental Research
Budget Activity Number KP 12 04 01 0

Prepared by the
Carbon Dioxide Information Analysis Center
Environmental Sciences Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6335
managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY

under contract DE-AC05-00OR22725

CONTENTS

LIST OF TABLES

Table **Page**

ABBREVIATIONS

CDIAC	Carbon Dioxide Information Analysis Center
CEC	cation exchange capacity
CLR	canopy light ratio
dbh	diameter at breast height
FTP	file transfer protocol
LAI	leaf area index
NDP	numeric data package
PAR	photosynthetically active radiation
QA	quality assurance
RelLAI	relative leaf area index
TDE	Throughfall Displacement Experiment
TDR	time-domain reflectometer
WBW	Walker Branch Watershed

ABSTRACT

Hanson, P. J., D. E. Todd, J. S. Riggs, M. E. Wolfe, and E. G. O'Neill. 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 pp.

This numeric data package provides data sets, and accompanying documentation, on site characterization, system performance, weather, species composition, and growth for the Throughfall Displacement Experiment, which was established in the Walker Branch Watershed of East Tennessee to provide data on the responses of forests to altered precipitation regimes. The specific data sets include soil water content and potential, coarse fraction of the soil profile, litter layer temperature, soil temperature, monthly weather, daily weather, hourly weather,
species composition of trees and saplings, mature tree and sapling annual growth, and relative leaf area index.

Fortran and SAS^{TM} access codes are provided to read the ASCII data files. The data files and this documentation are available without charge on a variety of media and via the Internet from the Carbon Dioxide Information Analysis Center (CDIAC).

Keywords: forests, growth, leaf area index, litter, sapling, soil, soil temperature, soil water content, soil water potential, tree, weather

1. BACKGROUND INFORMATION

INTRODUCTION

Models of global climate change predict that increasing levels of greenhouse gases in the atmosphere will (1) cause an increase in average global temperatures and (2) alter regional levels of precipitation. It is also predicted that the incidence of drought will increase with a warming global climate. Forests throughout the southeastern United States, where evapotranspiration demand is high and is predicted to increase as temperatures rise, would be particularly vulnerable to declines in annual precipitation. Potential responses of U.S. forests to future drought associated with climate change include a reduction in net primary production and stand water use, along with increased mortality of seedlings and saplings (Hanson and Weltzin 2000).

To provide data on the responses of forests to altered precipitation regimes, the Throughfall Displacement Experiment (TDE) was established in the Walker Branch Watershed (WBW) of East Tennessee (latitude 35º 58' N, longitude 84º 17' W). Funding for the TDE was provided by the Program for Ecosystem Research (**http://www.er.doe.gov/production/ober/GC/per.html**) of the U.S. Department of Energy's Office of Biological and Environmental Research.

Remotely sensed imagery of the WBW is available from the National Aeronautics and Space Administration (**http://modis-land.gsfc.nasa.gov/val/coresite.asp?SiteID=28** and **http://modis.gsfc.nasa.gov/MODIS/LAND/VAL/prove/forest/prove.html**) and from the U.S. Geological Survey (**http://edcdaac.usgs.gov/pathfinder/walker/gsm011na.htm**).

A detailed description of the TDE is provided by Hanson et al. (1998) and Hanson et al. (2001), both of which are included in Appendix A of this report. Experimental manipulation of hydrologic inputs at the TDE is accomplished by intercepting throughfall in approximately 2000 subcanopy troughs (0.3 × 5 m) suspended above the forest floor on a "dry" treatment plot and transferring the throughfall across a control plot for distribution onto a "wet" treatment plot. Each plot is 80 × 80 m in size. The treatments result in a 33% decrease in precipitation reaching the forest floor on the dry plot and a corresponding increase in precipitation on the wet plot. Reductions in soil moisture on the dry plot are expected to be equivalent to the driest growing seasons of the 1980's drought, which resulted in reduced tree growth of some species.

The site was chosen because of its uniform slope, consistent soils, and a reasonably uniform distribution of vegetation. The physical and chemical characteristics of the typic Paleudult soils (Fullerton cherty silt loam) of the TDE site are summarized in Appendix B. The forest community is dominated by white oak, chestnut oak, and red maple, but it contains more than 25 tree species (Appendix C). The past 25 years of research on the Walker Branch Watershed provide an important reference database against which to judge the outcomes of this large-scale field experiment.

MEASUREMENT METHODS

Soil Water Content and Potential

Soil water content (%, v/v) was measured with a Soil Moisture Equipment Corp.® TRASE SYSTEM time-domain reflectometer (TDR) following the procedure of Topp and Davis (1985) as documented for soils with high coarse-fraction content (Drungil et al. 1989). Three hundred and ten sampling locations were installed at an 8 × 8-m spacing across the site, giving more than 100 soil water monitoring locations per plot. At each location two pairs of TDR waveguides were installed in a vertical orientation (0 to 0.35 and 0 to 0.7 m). The surface (0 to 0.35 m) TDR measurements coincide with the zone of maxium root density in these soils. TDR measurements were obtained biweekly during the growing season and approximately monthly during the dormant season. The TDR soil water content measurements were adjusted for the coarse fraction of these soils and converted to soil water potentials using laboratory-derived soil moisture retention curves for the A, A/E, and E/B horizons (Hanson et al. 1998).

Soil Rock Content

Soil was sampled from depths of 0 to 30 and 30 to 60 cm in ~10-cm-diameter cylindrical cores with a total volume of 2430.96 cm^3. The soil coarse fraction was determined by weighing the material retained by a 2-mm sieve. To convert coarse-fraction mass to volume all rock (i.e., chert) was assumed to have a mean density of 2.3 g cm^{-3}. This density was based on laboratory observations for chert taken from the TDE samples.

Weather and Radiation

Weather data are collected as hourly means and logged on LiCor® LI-1000 data loggers housed in instrument enclosures located at one upslope and one downslope location per treatment plot and one enclosure in the nearby clearing. Measurements of incoming rainfall, irradiance (LiCor® LI-200SA pyranometer), and photosynthetic photon flux density (LiCor® LI-191SA quantum sensor) were obtained in a nearby clearing until 1998 when above-canopy observations were added to the ambient plot tower. Clearing data were used to represent “above-canopy” conditions for the experimental site for the years 1993–1997. Mean incident shortwave radiation was measured with an Eppley® precision spectral pyranometer located 44 m above the forest canopy (these data are not available for 1993 and 1994). Two tipping bucket rain gauges with 3-m extension troughs attached are installed on each plot to evaluate the amount of throughfall reaching the forest floor. Sub-canopy air temperatures (2 stations per treatment plot) are measured with thermistors at approximately 1 m height in a location shielded from direct solar radiation. Wind data for 1993 through 1997 are from a height of 37 m on the the Oak

Ridge Ameriflux tower (10 m above the canopy). A value of 1.5 m s^{-1} is used to fill in for missing hours for those years in the hourly weather data. Wind data for 1998 through 2000 are from the ambient plot tower on the TDE experimental site and the anemometer is nearer to the canopy (4 m above the canopy).

Litter Temperature

Self-contained Onset Computer® data loggers were deployed within the Oi litter layer during extensive periods in 1997–1998 and 2000. In 1997–1998, StowAway XTI08 sensors in the dry (×4) and ambient (×4) plots were used. The XTI08 sensors employed an external thermistor positioned inside litter decomposition bags that were located in the Oi horizon leaf litter from March 15, 1997, through February 6, 1998. StowAway TidbiT sensors were placed directly in the Oi layer of the dry (×4) and wet (×4) plots from January 27, 2000, to December 14, 2000.

Soil Temperature

From 1993 through 1997 hourly soil temperatures were measured at two depths (10 and 35 cm) at 2 locations in each treatment plot. LiCor® LI-1000-15 soil temperature thermistors were installed vertically from the surface to the specified depth. Data were automatically logged on six independent LiCor LI-1000 data loggers housed in instrument enclosures located at one upslope and one downslope location per treatment plot. No differences among treatment plots or slope positions were observed for temperatures at these depths, and the data were pooled as hourly site averages. Starting in 1998, soil temperature observations were obtained from Campbell Scientific® Model 107 soil temperature thermistors installed horizontally into the walls of an excavated and subsequently refilled soil pit. The probes were distributed at four depths in each pit (~10 cm, ~30 cm, ~45 cm, and one deep probe in the 60 to 100-cm range). Data were logged as hourly means of 5-second (for 1993–1997 data) or 1-minute (1998 and thereafter) observations on a Campbell Scientific® CR10X data logger.

Tree Mortality and Growth

Prior to the experiment and at approximately annual intervals thereafter, all trees greater than 0.1 m in diameter at 1.3 m height (diameter at breast height, dbh) were identified to species (762 trees). Presence/mortality was recorded annually. Annual diameter measurements were conducted with diameter tapes at tagged locations on all trees.

Tree heights and crown widths were measured directly on approximately one-third of the trees or derived from allometric relationships from a subset of the measured data. *Quercus* spp. and *Acer* spp.

were the major canopy dominants; *Liriodendron tulipifera* L. was a canopy dominant on the lower slope positions; and *Nyssa sylvatica* Marsh. and *Oxydendrum arboreum* [L.] D. C. were the predominant species occupying mid-canopy locations. In March of 1994, stand basal area averaged 21 m^2 ha^{-1} with nearly identical basal area on each plot. By December 1999, mean basal area across all plots had increased to 22.8 m^2 ha^{-1}.

Quercus alba L., *Q. prinus* L., *Acer rubrum* L., *L. tulipifera* L., and *N. sylvatica* Marsh. trees greater than 0.2 m dbh were fitted with dendrometer bands (170 trees) for biweekly measurements of stem circumference during each growing season. A single dendrometer measurement consists of duplicate digital caliper measurements (0.01 mm resolution) of the distance between two reference holes in stainless steel dendrometer bands (25.4 mm wide × 0.2 mm thick) installed around the circumference of each tree (McLaughlin and Downing 1996). 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 (mm^2 day^{-1} or mm^2 $year^{-1}$). Dendrometer bands were installed on the *Q. alba*, *Q. prinus*, and *A. rubrum* trees prior to the 1993 growing season, and bands for *L. tulipifera* and *N. sylvatica* were added in February of 1994. All dendrometer bands were installed 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).

Sapling Growth and Mortality

Starting in 1996 all saplings in 27 plots (8 × 8 m) distributed across the TDE experimental area (9 plots per treatment) were observed for survival and diameter (measured with a caliper) at marked locations on the stems. The preferred target height for diameter measurements was 1.3 m unless the sapling was too small, in which case 1 m was used instead. Figure 1 shows the distribution (random within rows). Each small block is an 8 × 8-m plot. The 27 plots, each

8 × 8 m, yielded a total of 1728 m^2 of monitored area, which was 9% of the total TDE experimental area. The number of saplings (trees < 0.1 m dbh) across the TDE area averaged 3073 ha^{-1} in 1994 and 2112 ha^{-1} in 1999. Saplings contributed an additional 3 and 2.6 m^2 ha^{-1} to total stand basal area in 1994 and 1999, respectively. *Acer rubrum* L. and *Cornus florida* L. combined to make up 59 percent of all saplings and 53 percent of the sapling basal area.

In February and March of 1994, 10 transects for observations of sapling growth and mortality were established across the three plots from lower- to upper-slope positions. Although other species were considered for these measurements, only *A. rubrum* and *C. florida* were distributed across the TDE in sufficient numbers for inclusion. Saplings ranged from 10 to 60 mm dbh with the majority from 10 to 40 mm. Height measurements were not included because the crowns were broad without predominant main shoots and because height growth was minimal in the low-light understory environment of our closed canopy stand. Starting at the time of spring leafout each year, biweekly measurements of stem diameter at a permanently marked location on each sapling's main stem (typically between 1 and 1.5 m above the ground) were conducted until sapling growth had ceased for that year. Each stem caliper measurement was the mean of three replicate diameter measurements made with a digital caliper (0.01 mm resolution) from three different angles around the marked point of measurement. The mean of replicate measures
from different angles was required to minimize the impact of noncircular stem cross sections. Sapling stem diameters were converted to basal area to express mean daily sapling growth rates per plant in mm^2 day^{-1}, or integrated annual sapling growth in mm^2 $year^{-1}$. Incremental growth of saplings that died in a given year were included in the calculation of that year's mean growth rate but excluded in all subsequent estimates of annual growth. Additional randomly chosen saplings were added to the measurement pool after the 1994, 1995, and 1996 growing seasons (to make up for mortality losses), but no additional plants were added to this observation set after that time.

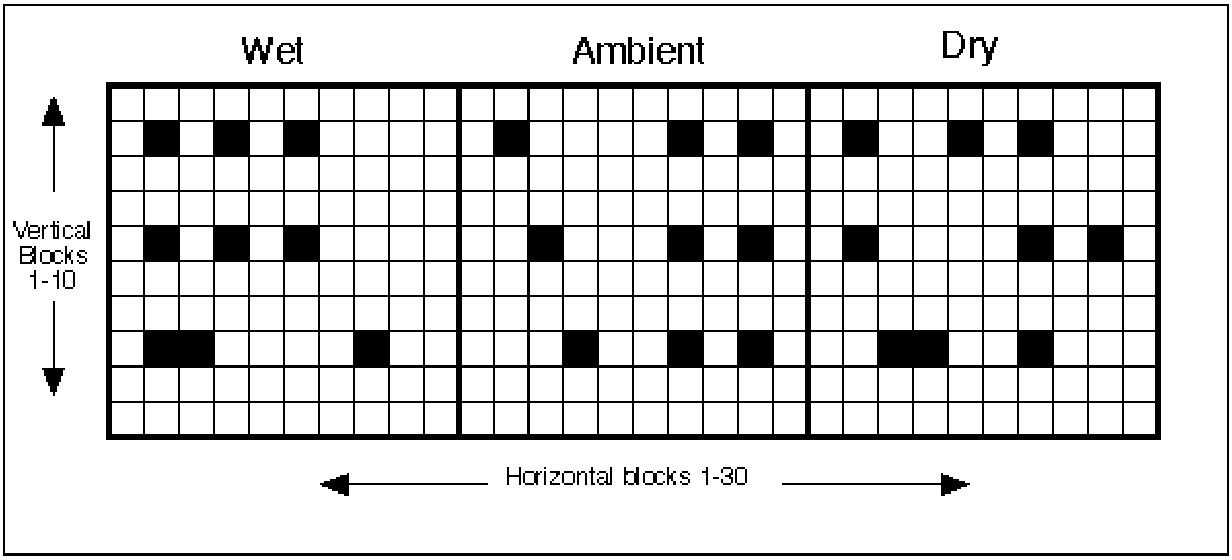


Figure 1. Distribution of plots for observation of survival and diameter of saplings at the TDE site.

Leaf Area Index

Seasonal patterns of stand leaf area development were determined from the ratio of understory to overstory light penetration. This canopy light ratio (CLR; Equation 1) was calculated as 1 minus the ratio of the daily sum of understory photosynthetically active radiation (PAR_u; PAR at 1.5 m) to the daily sum of overstory incident PAR (PAR_o):

$$\mathrm{CLR} = 1 - (\mathrm{PAR}_u/\mathrm{PAR}_o) \qquad \text{Eq. 1}$$

Because of the presence of tree boles and branches, pre-leaf out and post-senescence baselines for the CLR were not zero. Therefore, to express the CLR on a 0–1 scale it was necessary to adjust the ratio for the light penetration during leafless periods as shown in Equation 2:

$$\text{RelLAI} = (\text{Observed CLR} - \text{baseline})/(\text{Maximum CLR} - \text{baseline}) \qquad \text{Eq. 2}$$

where RelLAI is the relative leaf area index on the 0–1 scale for a given date. However, because the baseline ratio resulting from the presence of boles and branches changed with solar elevation, we found it necessary to use more than one baseline for the calculation of the seasonal pattern of RelLAI. Although the baseline CLR in the absence of leaves would vary continuously with solar elevation, we found that use of the pre-leafout baseline for days 80 through 180 and the post-senescence baseline for days 181 through 350 yielded an acceptable RelLAI pattern. It is important to note that the RelLAI values are representative of the development of leaf area, not leaf mass (i.e., they may overpredict the rate of annual leaf mass accumulation). Approximations of leaf mass development or a direct estimate of leaf are index (LAI) could also be made from the same data using a light extinction approach as described by Hutchinson and Baldocchi (1989).

Data Logging

Environmental data for the TDE were logged on Campbell Scientific® CR10X data loggers located on each of the treatment plots. All loggers were interfaced with a Campbell Scientific® MD9 coaxial multidrop interface, and data from all loggers were remotely accessed weekly via Campbell Scientific® COM200 modem and cellular telephone. As a backup to remote data downloads, the logged data were also stored in Campbell Scientific® SM192 nonvolatile circular memory with the capacity to hold approximately one month's data for the configuration used here. The loggers and associated instrumentation operated off three 12-volt, deep-cycle marine batteries wired in parallel. The batteries were trickle-charged from solar panels (Solarex® 55 watts @ 17.4 volts; with a metered Morningstar® PS30M photovoltaic controller, 30-amp PV current @ 12 volts) installed on towers above the forest canopy. Sensors were connected to the CR10X data logger via a standard wiring panel and two Campbell Scientific® AN416 multiplexer modules.

An example data program for the CR10X data logger editor and the data logger download file for the TDE ambient plot and its instruments are included in this numeric data package (NDP) as files **tdeambi.csi** and **tdeambi.dld**, respectively. The example program includes two sampling tables. The majority of the instrumentation is queried once per minute and logged as hourly means or sums as a part of the first sampling table, and a second samling table is included to query heat dissipation matric potential sensors (Campbell Scientific® Model 229) twice a day (noon and midnight). Table 1 lists the measurement interval, logging interval, and type of sensors being logged on the TDE ambient plot as of December 2000.

Table 1. Environmental sensors attached to the TDE ambient plot CR10X data logger as of December 2000

Sensor	Units	Number of sensors	Measurement interval	Logging interval
Time stamp				
Year	y	n/a	1 h	hourly
Day	d	n/a	1 h	hourly
Time	hh:mm	n/a	1 h	hourly
Fractional day of year	d	n/a	1 h	hourly
Battery voltage	v	n/a	1 h	hourly
Above-canopy sensors				
Pyranometer (LiCor® LI-200SA)	W m^{-2} s^{-1}	1	1 min	hourly mean
Wind speed (Campbell Scientific® 014A)	m s^{-1}	1	1 min	hourly mean
Rainfall (Campbell Scientific® TE525MM)	mm	1	continuous	hourly sum
Quantum (LiCor® LI-191SA)	Fmol m^{-2} s^{-1}	2	1 min	hourly mean
Air temperature/relative humidity (Rotronics® 101)	deg C/%	1	1 min	hourly mean
Understory sensors				
Understory rainfall[a] (Campbell Scientific® TE525MM)	mm	1	continuous	hourly sum
Quantum (LiCor® LI-191SA)	Fmol m^{-2} s^{-1}	1	1 min	hourly mean
Air temperature/relative humidity (Rotronics® 101)[a]	deg C/%	1	1 min	hourly mean
Soil and litter sensors				
Soil temperature (Campbell Scientific® 107)	deg C	4	1 min	hourly mean
Soil water content (Campbell Scientific® 615)	% v/v	8	1 min	hourly mean
Litter water content (DC half-bridge)[a]	g g^{-1}	8	1 min	hourly mean
Soil matric potential	MPa	8	12 h	twice daily
Plant measurements				
Sapflow[a]	deg C	8	1 min	hourly mean

Sensor	Units	Number of sensors	Measurement interval	Logging interval
Sapflow voltage[a] (Dynamax® thermal dissipation sap velocity probe)	V	1	1 min	hourly mean

[a] data not included in this numeric data package.

This NDP provides datasets, and accompanying documentation, on site characterization, system performance, weather, species composition, and growth. Related NDPs are planned on physiology, decomposition, and nutrient cycling.

2. APPLICATIONS OF THE DATA

These data are useful for quantifying certain responses of temperate forest ecosystems (litter and soil water content, growth, mortality) to changes in precipitation patterns. Other datasets from the TDE will be useful for quantifying other aspects of ecosystem response (e.g., physiology, decomposition, nutrient cycling).

Data from the TDE have been used in published studies of the effects of altered water regimes on forest root systems (Joslin et al. 2000) and sapling and large-tree growth and mortality (Hanson et al. 2001), and a wide variety of process-based studies (see Appendix D for TDE publications).

3. DATA LIMITATIONS AND RESTRICTIONS

Users should be aware of limitations to the data as a result of suspect values. The quality-assurance checks performed by CDIAC, and the results of those checks, are described in Section 4.

In the weather files, some reported values of relative humidity (in files **mweather.dat**, **dweather.dat**, **hw9399.dat**, and **hw00.dat**) exceed 100%; this is physically impossible. However, it is not yet known how these values arose nor how to adjust the data.

Some values of relative leaf area (in file **rellai.dat**) were suspiciously low, such as the value of 0.44 on day 289 in 1998. Most such values occur in the fall; a lower sun angle may contribute to these low values. A curve-fitting approach may be appropriate to analyze the patterns of leaf senescence.

Hourly weather data were checked by the data contributors for errors and missing data. If bad or missing data were found, approximate replacement data were obtained from other weather data sources in the area, if possible, to provide the most complete data set.

If TDE shortwave radiation data are needed for model input, the values for SWISIS should be used instead of the LiCor® pyranometer data. Both are in good agreement for most years, but the TDE pyranometer data for 1998 and 2000 do not agree very well with the SWISIS data (mean of 5 observations) distributed across the reservation.

The issue of pseudo-replication in the experimental design is addressed by Hanson et al. (1998) and Hanson et al. (2001) (Appendix A).

In addition to the above considerations, users should be aware that there is some evidence of minor effects of the experimental infrastructure (specifically, the precipitation-collection equipment) on the microclimate of the “dry” treatment plot.

4. QUALITY-ASSURANCE CHECKS AND DATA-PROCESSING ACTIVITIES PERFORMED BY CDIAC

An important part of the data packaging process at CDIAC involves the quality assurance (QA) of data before distribution. To guarantee data of the highest possible quality, CDIAC performs extensive QA checks, examining the data for completeness, reasonableness, and accuracy.

Comma-delimited files provided by the data contributors were imported into Microsoft Excel® for QA checks (and, ultimately, converted to space-delimited ascii files for archiving). Files were renamed when necessary, for consistency. Variable names were made consistent across files, for simplicity of documentation and analysis.

The file soiltemp.txt provided by the data contributor was divided into two files, **st9398.dat** (data from 1993 through 1998) and **st9900.dat** (data from 1999 through 2000). Sixteen tdr*.txt files (one set for each of two depths, 35 and 70 cm, and for each year from 1993 through 2000) were combined into one **tdr.dat** file. For consistency with other files, in file **tdr.dat** integer values 1, 2, and 3 for the variable TREAT were replaced by character values W, A, and D, respectively; and values 1, 2, and 3 for the variable SLOPE were replaced by values B, M, and U, respectively. Eight monthly and eight daily weather files (one monthly and one daily file for each year from 1993 through 2000) were combined into a single **mweather.dat** file and a single **dweather.dat** file, respectively. Seven hourly weather files (for the years 1993 through 1999) were combined into a single **hw9399.dat** file.

The format of all values was checked for improper entries.

Several files (e.g., **atree.dat**) were reformatted by adding variables for year, depth, etc., but eliminating variables that were a combination of year, depth, etc., and another variable (e.g., growth), thereby reducing the total number of variables, resulting in a "narrower" but "longer" file.

For all variables in all files, the range of values was checked for impossible or suspiciously large or small values, such MONTH >12 or values of water potential (e.g., variable A35WP in file **sw.dat**) >0 MPa. Values of relative humidity apparently exceeding 100% are discussed in
Section 3.

Comparisons and X-Y scattergrams were used to check for outliers and impossible or unlikely combinations. For example, file **mweather.dat** was inspected to ensure that, for air temperature, relative humidity, and soil temperature, the minimum did not exceed the mean, which in turn did not exceed the maximum; no observations failed this test. Scattergrams were plotted and visually examined to check the correlation between PYRAN and QUAN; and ATMIN and STMIN, ATMEAN and STMEAN, and ATMAX and STMAX (minimum, mean, and maximum air and soil temperatures) in file **mweather.dat**; no obvious outliers were detected.

The following lists the specific data-quality checks by file:

File **sw.dat**
range checks for all variables
scattergrams: DOY v RDOY, RDOY v DATE

Result: No suspect data were identified.

File **nine.dat**
range checks for all variables
scattergrams: DOY v RDOY

Result: No suspect data were identified.

File **tdr.dat**
range checks for all variables

Result: No suspect data were identified.

File **rocks.dat**
range checks for all variables

Result: No suspect data were identified.

File **littert.dat**

range checks for all variables

scattergram: FDOY v DOY

Result: No suspect data were identified.

File **st9398.dat** and **st9900.dat**

range checks for all variables

Result: No suspect data were identified.

File **mweather.dat**

range checks for all variables

comparisons: ATMIN # ATMEAN # ATMAX, RHMIN # RHMEAN # RHMAX, STMIN # STMEAN # STMAX

scattergrams: PYRAN v QUAN, ATMIN v STMIN, ATMEAN v STMEAN, ATMAX v STMAX

Result: No suspect data were identified (other than some values of RHMIN, RHMEAN, and RHMAX >100%).

File **dweather.dat**

range checks for all variables

comparisons: ATMIN # ATMEAN # ATMAX, RHMIN # RHMEAN # RHMAX, STMIN # STMEAN # STMAX

scattergrams: PYRAN v QUAN, RADMEAN v QUAN, ATMIN v STMIN, ATMEAN v STMEAN, ATMAX v STMAX

Result: No suspect data were identified (other than some values of RHMIN, RHMEAN, and RHMAX >100%).

File **hw9399.dat**

range checks for all variables

comparisons: UQUAN # QUAN

Result: Some values of RH >100%; 1502 occurrences of UQUAN > QUAN were detected (with values of UQUAN minus QUAN ranging from 1 to 366 µmol m^{-2} s^{-1}, typically during periods of low light conditions), tentatively attributed by the data contributor to random error in the sensors or data loggers; these data were not adjusted.

File **hw00.dat**

range checks for all variables
comparisons: UQUAN # QUAN
scattergrams: PYRAN v QUAN, UQUAN v QUAN, HOY v DFOY, AT v ST

Result: Some values of RH >100%; 97 occurrences of UQUAN > QUAN were detected (with values of UQUAN minus QUAN ranging from 1 to 6 µmol m^{-2} s^{-1}), as with file **hw9399.dat**.

File **comptree.dat**

range checks for all variables
check for duplicate values of ID
check SPC values against list of species

Result: No suspect data were identified.

File **compsap.dat**

range checks for all variables

Result: No suspect data were identified.

File **atree.dat**

range checks for all variables
check for duplicate values of ID
check SPC values against list of species

Result: No suspect data were identified.

File **asapling.dat**

range checks for all variables
check for duplicate values of ID
check SPC values against list of species

Result: No suspect data were identified.

File **rellai.dat**

range checks for all variables
Relative LAI values between 0 and 1

Result: All years had some values of relative LAI that were outside the range of 0.00 to 1.00 (minimum of -0.33 in 1994 and maximum of 1.05 in 1998); per instruction from the data contributor, these were set to missing. A few anomalously low values, such as 0.44 on day 289 in 1998, were detected; per instruction from the data contributor, these were not changed.

5. REFERENCES

Drungil, C. E. C., K. Abt, and T. J. Gish. 1989. Soil moisture determination in gravelly soils with time domain reflectometry. *Transactions Am. Soc. Agric. Eng*. 32:177–180.

Hanson, P. J., D. E. Todd, and J. S. Amthor. 2001. A six-year study of sapling and large-tree growth and mortality responses to natural and induced variability in precipitation and throughfall. *Tree Physiology* 21:345–358.

Hanson, P. J., D. E. Todd, M. A. Huston, J. D. Joslin, J. L. Croker, and R. M. Augé. 1998. *Description and field performance of the Walker Branch Throughfall Displacement Experiment: 1993-1996*. ORNL/TM-13586. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Hanson, P. J., and J. F. Weltzin. 2000. Drought disturbance from climate change: Response of United States forests. *Science of the Total Environment* 262:205–220.

Hutchinson, B. A., and D. D. Baldocchi. 1989. Forest meteorology, pp. 21–95. In D. W. Johnson and R. I. Van Hook (eds.), *Analysis of Biogeochemical Cycling Processes in Walker Branch Watershed*, Springer-Verlag, New York.

Joslin, J. D., M. H. Wolfe, and P. J. Hanson. 2000. Effects of altered water regimes on forest root systems. *New Phytologist* 147:117–129.

Keeland, B. D., and R. R. Sharitz. 1993. Accuracy of tree growth measurements using dendrometer bands. *Canadian Journal of Forestry Research* 23:2454–2457.

McLaughlin, S. B., and D. J. Downing. 1996. Interactive effects of control ozone and climate measured on growth of mature loblolly pine trees. *Canadian Journal of Forestry Research* 26:670–681.

Topp, G. C., and J. L. Davis. 1985. Measurement of soil water content using time domain reflectometry (TDR): A field evaluation. *Soil Science Society of America Journal* 49:19–24.

6. HOW TO OBTAIN THE DATA AND DOCUMENTATION

This database (NDP-078A) is available free of charge from CDIAC. The files are available, via the Internet, from CDIAC's Web site (**http://cdiac.esd.ornl.gov**) or from CDIAC's anonymous FTP (file transfer protocol) area (**cdiac.esd.ornl.gov**) as follows:

1. FTP to cdiac.esd.ornl. gov (128.219.24.36).
2. Enter "ftp" as the user id.

3. Enter your electronic mail address as the password (e.g., fred@zulu. org).
4. Change to the directory "pub/ndp078a" (i.e., use the command "cd pub/ndp078a").
5. Set ftp to get ASCII files by using the ftp "ascii" command.
6. Retrieve the ASCII database documentation file by using the ftp "get ndp078a.txt" command.
7. Retrieve the ASCII data files by using the ftp "mget *.dat" and "mget tedambi.*" commands.
8. Exit the system by using the ftp "quit" command.

For **non-Internet data acquisitions** (e.g., floppy diskette or CD-ROM), or for additional information, contact:

Carbon Dioxide Information Analysis Center
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6335, U. S. A.

Telephone: 1-865-574-3645
Telefax: 1-865-574-2232
Email: cdiac@ornl.gov

7. LISTING OF FILES PROVIDED

This database consists of 19 ASCII files: this text documentation file (**ndp078a.txt**, File 1) and 18 data files (Table 2).

Table 2. Files in this numeric data package

File number	File name	File size (bytes)	File description
1	ndp078a.txt	98k	Descriptive file (i.e., this document)
2	tdeambi.csi	16k	Example data program for the CR10X data logger editor for the TDE ambient plot and its instruments
3	tdeambi.dld	4k	Example data logger download file for the TDE ambient plot and its instruments
4	sw.dat	13k	Mean soil water content and potential (1993–2000), by date, treatment, and depth
5	nine.dat	14k	Mean soil water content and potential for the 0- to 35-cm depth increment (1993–2000), by date, treatment and slope position
6	tdr.dat	2.1M	Gridded soil water content
7	rocks.dat	12k	Coarse fraction for the 0- to 30- and 30- to 60-cm portions of the soil profile
8	littert.dat	824k	Litter layer temperature
9	st9398.dat	1.9M	Soil temperature for 1993–1998
10	st9900.dat	1.9M	Soil temperature for 1999–2000
11	mweather.dat	7k	Monthly weather data
12	dweather.dat	265k	Daily weather data
13	hw9399.dat	4.6M	Hourly weather data for 1993–1999
14	hw00.dat	678k	Hourly weather data for 2000
15	comptree.dat	68k	Species composition: Trees (>10-cm dbh)
16	compsap.dat	27k	Species composition: Saplings (<10-cm dbh and >1 m tall)
17	atree.dat	53k	Mature tree annual growth
18	asapling.dat	88k	Sapling annual growth
19	rellai.dat	37k	Seasonal patterns of relative leaf area index

8. DESCRIPTION OF THE DOCUMENTATION FILE

ndp078a.txt (File 1)

This file is identical to this document.

9. DESCRIPTION, FORMAT, AND PARTIAL LISTINGS OF THE ASCII DATA FILES

Table 3 describes the format and contents of the ASCII data file **sw.dat (File 4)** distributed with this numeric data package.

Table 3. Contents and format of sw.dat (File 4)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
DATE	Character	18	1	18	n/a	Measurement date (month, day, year)
RDOY	Integer	5	19	23	d	Running day of the year (days since January 1, 1993)
DOY	Integer	4	24	27	d	Day of the year (1 = 1 January, 365 or 366 = 31 December)
W35WC	Real	5	28	32	% v/v	Mean ‘wet’ plot water content of the 0- to 35-cm depth increment
A35WC	Real	5	33	37	% v/v	Mean ‘ambient’ plot water content of the 0- to 35-cm depth increment
D35WC	Real	5	38	42	% v/v	Mean ‘dry’ plot water content of the 0- to 35-cm depth increment
W35WP	Real	6	43	48	MPa	Mean ‘wet’ plot water potential of the 0- to 35-cm depth increment
A35WP	Real	6	49	54	MPa	Mean ‘ambient’ plot water potential of the 0- to 35-cm depth increment

Table 3 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
D35WP	Real	6	55	60	MPa	Mean ‘dry’ plot water potential of the 0- to 35-cm depth increment
W70WC	Real	5	61	65	% v/v	Mean ‘wet’ plot water content of the 0- to 70-cm depth increment
A70WC	Real	5	66	70	% v/v	Mean ‘ambient’ plot water content of the 0- to 70-cm depth increment
D70WC	Real	5	71	75	% v/v	Mean ‘dry’ plot water content of the 0- to 70-cm depth increment
W3570WC	Real	5	76	80	% v/v	Mean ‘wet’ plot water content of the 35- to 70-cm depth increment
A3570WC	Real	5	81	85	% v/v	Mean ‘ambient’ plot water content of the 35- to 70-cm depth increment
D3570WC	Real	5	86	90	% v/v	Mean ‘dry’ plot water content of the 35- to 70-cm depth increment
W3570WP	Real	6	91	96	MPa	Mean ‘wet’ plot water potential of the 35- to 70-cm depth increment
A3570WP	Real	6	97	102	MPa	Mean ‘ambient’ plot water potential of the 35- to 70-cm depth increment

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
D3570WP	Real	6	103	108	MPa	Mean ‘dry’ plot water potential of the 35- to 70-cm depth increment

The missing-value indicators in this file are -9.9 for variables A35WC, D35WC, W70WC, A70WC, D70WC, W3570WC, A3570WC, and D3570WC; and -9.99 for variables A35WP, D35WP, W3570WP, A3570WP, and D3570WP.

First two data records:

```
  January 14, 1993   14  14 25.5 25.4 24.8 -0.04 -0.04 -0.04 26.2 26.6 26.5
27.7 28.6 29.0 -0.02 -0.02 -0.02
 February 24, 1993   55  55 26.6 25.6 25.1 -0.03 -0.04 -0.04 26.0 25.8 26.4
26.3 26.8 28.5 -0.03 -0.03 -0.02
```

Last two data records:

```
  November 1, 2000 2862 306  6.6 -9.9  5.6 -1.83 -9.99 -2.77 -9.9 -9.9 -9.9
-9.9 -9.9 -9.9 -9.99 -9.99 -9.99
 December 15, 2000 2906 350 23.0 23.4 22.4 -0.05 -0.05 -0.06 23.8 22.4 21.9
24.6 21.4 21.4 -0.04 -0.06 -0.06
```

Table 4 describes the format and contents of the ASCII data file **nine.dat (File 5)** distributed with this numeric data package.

Table 4. Contents and format of nine.dat (File 5)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
DOY	Integer	4	6	9	d	Day of the year (1 = 1 January, 365 or 366 = 31 December)
RDOY	Integer	5	10	14	d	Running day of the year (days since January 1, 1993)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
WBWC	Real	5	15	19	% v/v	Mean water content of the 0- to 35-cm depth increment of the bottom wet plot location
WMWC	Real	5	20	24	% v/v	Mean water content of the 0- to 35-cm depth increment of the middle wet plot location

Table 4 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
WUWC	Real	5	25	29	% v/v	Mean water content of the 0- to 35-cm depth increment of the upper wet plot location
ABWC	Real	5	30	34	% v/v	Mean water content of the 0- to 35-cm depth increment of the bottom ambient plot location
AMWC	Real	5	35	39	% v/v	Mean water content of the 0- to 35-cm depth increment of the middle ambient plot location
AUWC	Real	5	40	44	% v/v	Mean water content of the 0- to 35-cm depth increment of the upper ambient plot location
DBWC	Real	5	45	49	% v/v	Mean water content of the 0- to 35-cm depth increment of the bottom dry plot location
DMWC	Real	5	50	54	% v/v	Mean water content of the 0- to 35-cm depth increment of the middle dry plot location

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
DUWC	Real	5	55	59	% v/v	Mean water content of the 0- to 35-cm depth increment of the upper dry plot location
WBWP	Real	7	60	66	MPa	Mean water potential of the 0- to 35-cm depth increment of the bottom wet plot location

Table 4 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
WMWP	Real	7	67	73	MPa	Mean water potential of the 0- to 35-cm depth increment of the middle wet plot location
WUWP	Real	7	74	80	MPa	Mean water potential of the 0- to 35-cm depth increment of the upper wet plot location
ABWP	Real	7	81	87	MPa	Mean water potential of the 0- to 35-cm depth increment of the bottom ambient plot location
AMWP	Real	7	88	94	MPa	Mean water potential of the 0- to 35-cm depth increment of the middle ambient plot location
AUWP	Real	7	95	101	MPa	Mean water potential of the 0- to 35-cm depth increment of the upper ambient plot location
DBWP	Real	7	102	108	MPa	Mean water potential of the 0- to 35-cm depth increment of the bottom dry plot location
DMWP	Real	7	109	115	MPa	Mean water potential of the 0- to 35-cm depth increment of the middle dry plot location
DUWP	Real	7	116	122	MPa	Mean water potential of the 0- to 35-cm depth increment of the upper dry plot location

The missing-value indicators in this file are -9.9 for variables WBWC, WMWC, WUWC, ABWC, AMWC, AUWC, DBWC, DMWC, and DUWC; and -9.999 for variables WBWP, WMWP, WUWP, ABWP, AMWP, AUWP, DBWP, DMWP, and DUWP.

First two data records:

```
 1993  14   14 26.5 25.9 24.4 26.2 24.6 25.4 24.2 25.5 24.7 -0.037 -0.039
-0.043 -0.037 -0.045 -0.036 -0.044 -0.038 -0.039
 1993  55   55 27.1 26.7 26.5 26.7 24.5 25.4 24.9 25.6 25.1 -0.035 -0.035
-0.033 -0.035 -0.045 -0.036 -0.040 -0.037 -0.037
```

Last two data records:

```
 2000 306 2862  8.1 -9.9  5.0 -9.9 -9.9 -9.9  6.2 -9.9  4.9 -1.162 -9.999
-3.641 -9.999 -9.999 -9.999 -2.104 -9.999 -3.632
 2000 350 2906 24.7 22.1 22.3 24.3 23.1 22.9 20.6 22.0 19.9 -0.046 -0.063
-0.058 -0.047 -0.054 -0.050 -0.073 -0.060 -0.077
```

Table 5 describes the format and contents of the ASCII data file **tdr.dat (File 6)** distributed with this numeric data package.

Table 5. Contents and format of tdr.dat (File 6)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
DOY	Integer	4	6	9	d	Day of the year (1 = 1 January, 365 or 366 = 31 December)
DEPTH	Integer	3	10	12	cm	Depth interval (35 = 0–35 cm, 70 = 0–70 cm)
TREAT	Character	2	13	14	n/a	Treatment (W = wet, A = ambient, D = dry)
SLOPE	Character	2	15	16	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	3	17	19	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	20	22	arbitrary units	X coordinate position across the slope
YM	Integer	3	23	25	m	Y coordinate position up/down the slope
XM	Integer	4	26	29	m	X coordinate position across the slope
SWC	Real	5	30	34	% v/v	Soil water content

The missing-value indicator in this file is -9.9 for variable SWC.

First two data records:

```
1993  14 35W B   1  1  0   0 17.8
1993  14 35W B   1  2  0   8 26.6
```

Last two data records:

```
2000 350 70D U  10 30 72 232 22.0
2000 350 70D U  10 31 72 240 22.7
```

Table 6 describes the format and contents of the ASCII data file **rocks.dat (File 7)** distributed with this numeric data package.

Table 6. Contents and format of rocks.dat (File 7)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
TREAT	Character	2	1	2	n/a	Treatment (W = wet, A = ambient, D = dry)
SLOPE	Character	2	3	4	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	3	5	7	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	8	10	arbitrary units	X coordinate position across the slope
CFMASS30	Integer	5	11	15	g	Mass of rocks (mostly chert) at depth of 0–30 cm
CFVOL30	Real	6	16	21	cm^3	Volume of the rocks at depth of 0–30 cm
CFPCT30	Real	5	22	26	% v/v	Percent coarse fraction by volume at depth of 0–30 cm
CFMASS60	Integer	5	27	31	g	Mass of rocks (mostly chert) at depth of 30–60 cm
CFVOL60	Real	6	32	37	cm^3	Volume of the rocks at depth of 30–60 cm
CFPCT60	Real	5	38	42	% v/v	Percent coarse fraction by volume at depth of 30–60 cm

The missing-value indicators in this file are -999 for variables CFMASS30 and CFMASS60, -99.9 for variables CFVOL30 and CFVOL60, and -9.9 for variables CFPCT30 and CFPCT60.

First two data records:

```
W B   2  1 -999 -99.9 -9.9 -999 -99.9 -9.9
W B   2  2  475 206.5  8.5  697 303.0 12.5
```

Last two data records:

```
D U  10 30  651 283.0 11.6  734 319.1 13.1
D U  10 31 -999 -99.9 -9.9 -999 -99.9 -9.9
```

Table 7 describes the format and contents of the ASCII data file **littert.dat (File 8)** distributed with this numeric data package.

Table 7. Contents and format of littert.dat (File 8)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
DOY	Integer	4	6	9	month	Day of the year (1 = 1 January, 365 or 366 = 31 December)
DFOY	Real	7	10	16	d	Day fraction of the year
TREAT	Character	2	17	18	n/a	Treatment (W = wet, A = ambient, D = dry)
LITTERT	Real	6	19	24	deg C	Litter temperature

The missing-value indicator in this file is -9.9 for variable LITTERT.

First two data records:

```
1997  21  21.66 A  12.2
1997  21  21.70 A   9.9
```

Last two data records:

```
2000 349 349.50 D   6.9
2000 349 349.54 D   7.4
```

Table 8 describes the format and contents of the ASCII data file **st9398.dat (File 9)** distributed with this numeric data package.

Table 8. Contents and format of st9398.dat (File 9)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
MOY	Integer	3	6	8	month	Month of the year (1 = January, ..., 12 = December)
DOY	Integer	4	9	12	d	Day of the year (1 = 1 January, 365 or 366 = 31 December)
DFOY	Real	7	13	19	d	Day fraction of the year
HOY	Integer	5	20	24	h	Hour of the year
ST10	Real	6	25	30	deg C	Soil temperature at depth = 10 cm
ST35	Real	6	31	36	deg C	Soil temperature at depth = 35 cm

The missing-value indicators in this file are -99.9 for variables ST10 and ST35.

First two data records:

```
1993  1   1   1.00    1   7.0   7.0
1993  1   1   1.04    2   7.0   7.0
```

Last two data records:

```
1998 12 366 366.92 8783 -99.9 -99.9
1998 12 366 366.96 8784 -99.9 -99.9
```

Table 9 describes the format and contents of the ASCII data file **st9900.dat (File 10)** distributed with this numeric data package.

Table 9. Contents and format of st9900.dat (File 10)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
MOY	Integer	3	6	8	month	Month of the year (1 = January, ..., 12 = December)
DOY	Integer	4	9	12	d	Day of the year (1 = 1 January, 365 or 366 = 31 December)
DFOY	Real	7	13	19	d	Day fraction of the year
HOY	Integer	5	20	24	h	Hour of the year
ST10	Real	8	25	32	deg C	Soil temperature at depth = 10 cm
ST27	Real	8	33	40	deg C	Soil temperature at depth = 27 cm
STW6	Real	6	41	46	deg C	Soil temperature for wet plot, depth = 6 cm
STW31	Real	6	47	52	deg C	Soil temperature for wet plot, depth = 31 cm
STW55	Real	6	53	58	deg C	Soil temperature for wet plot, depth = 55 cm
STW72	Real	6	59	64	deg C	Soil temperature for wet plot, depth = 72 cm
STA7	Real	6	65	70	deg C	Soil temperature for ambient plot, depth = 7 cm
STA32	Real	6	71	76	deg C	Soil temperature for ambient plot, depth = 32 cm
STA59	Real	6	77	82	deg C	Soil temperature for ambient plot, depth = 59 cm
STA100	Real	6	83	88	deg C	Soil temperature for ambient plot, depth = 100 cm
STD9	Real	6	89	94	deg C	Soil temperature for dry plot, depth = 9 cm
STD30	Real	6	95	100	deg C	Soil temperature for dry plot, depth = 30 cm
STD45	Real	6	101	106	deg C	Soil temperature for dry plot, depth = 45 cm
STD63	Real	6	107	112	deg C	Soil temperature for dry plot, depth = 63 cm

The missing-value indicators in this file are -9.999 for variables ST10 and ST27, and -9.99 for variables STW6, STW31, STW55, STW72, STA7, STA32, STA59, STA100, STD9, STD30, STD45, and STD63.

First two data records:

```
 1999  1   1   1.00    1  6.1571  7.4550 -9.99 -9.99 -9.99 -9.99 -9.99 -9.99 -
9.99 -9.99 -9.99 -9.99 -9.99 -9.99
 1999  1   1   1.04    2  6.0109  7.3718 -9.99 -9.99 -9.99 -9.99 -9.99 -9.99 -
9.99 -9.99 -9.99 -9.99 -9.99 -9.99
```

Last two data records:

```
 2000 12 366 366.92 8783 -9.9999 -9.9999  3.10  5.50  6.90  7.40  4.20  7.00
8.20  9.70  3.90  5.80  6.80  7.60
 2000 12 366 366.96 8784 -9.9999 -9.9999  3.00  5.50  6.90  7.40  4.10  7.00
8.20  9.70  3.80  5.80  6.80  7.60
```

Table 10 describes the format and contents of the ASCII data file **mweather.dat (File 11)** distributed with this numeric data package.

Table 10. Contents and format of mweather.dat (File 11)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
MONTH	Integer	3	6	8	month	Month (1 = January, ..., 12 = December)
QUAN	Integer	5	9	13	mol m^{-2}	Integrated incident photosynthetically active radiation (PAR)
PYRAN	Integer	4	14	17	MW m^{-2}	Integrated incident total radiation
RAIN	Integer	4	18	21	mm	Monthly total rain (sum of hourly values)
ATMIN	Real	6	22	27	deg C	Monthly 1-h minimum air temperature
ATMEAN	Real	5	28	32	deg C	Monthly 1-h mean air temperature
ATMAX	Real	5	33	37	deg C	Monthly 1-h maximum air temperature
RHMIN	Real	5	38	42	%	Monthly 1-h minimum relative humidity
RHMEAN	Real	5	43	47	%	Monthly 1-h mean relative humidity
RHMAX	Real	6	48	53	%	Monthly 1-h maximum relative humidity
STMIN	Real	5	54	58	deg C	Monthly 1-h minimum soil temperature (15-cm depth)
STMEAN	Real	5	59	63	deg C	Monthly 1-h mean soil temperature (15-cm depth)
STMAX	Real	5	64	68	deg C	Monthly 1-h maximum soil temperature (15-cm depth)
WIND	Real	6	69	74	m/s	Mean daily wind speed

The missing-value indicator in this file is -9.99 for variable WIND.

First two data records:

```
1993  1  384 186 101  -3.3  5.5 16.5 21.5 76.8 101.5  5.0  6.1  7.5 -9.99
1993  2  488 241  50 -11.7  3.8 20.0 16.5 67.9 101.6  6.0  7.8  9.5 -9.99
```

Last two data records:

```
2000 11  439 232 104  -6.5  8.0 25.1 15.0 68.4 100.0  6.7 12.2 17.8  1.40
2000 12  376 189  75 -12.4 -0.5 11.5 31.7 71.2  99.8  3.2  6.7 10.0  1.60
```

Table 11 describes the format and contents of the ASCII data file **dweather.dat (File 12)** distributed with this numeric data package.

Table 11. Contents and format of dweather.dat (File 12)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
DOY	Integer	4	6	9	d	Day of the year (1 = 1 January, ..., 365 or 366 = 31 December)
QUAN	Real	6	10	15	mol m^{-2}	Integrated incident photosynthetically active radiation (PAR)
PYRAN	Real	6	16	21	MW m^{-2}	Integrated incident total radiation
RADMEAN	Real	10	22	31	W m^{-2}	Mean daily radiation
RAIN	Integer	6	32	37	mm	Monthly total rain (sum of hourly values)
ATMIN	Real	6	38	43	deg C	Monthly 1-h minimum air temperature
ATMEAN	Real	6	44	49	deg C	Monthly 1-h mean air temperature
ATMAX	Real	5	50	54	deg C	Monthly 1-h maximum air temperature
RHMIN	Real	6	55	60	%	Monthly 1-h minimum relative humidity

Table 11 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
RHMEAN	Real	6	61	66	%	Monthly 1-h mean relative humidity
RHMAX	Real	6	67	72	%	Monthly 1-h maximum relative humidity
STMIN	Real	5	73	77	deg C	Monthly 1-h minimum soil temperature (15-cm depth)
STMEAN	Real	5	78	82	deg C	Monthly 1-h mean soil temperature (15-cm depth)
STMAX	Real	5	83	87	deg C	Monthly 1-h maximum soil temperature (15-cm depth)
WIND	Real	5	88	92	m/s	Mean hourly wind speed

The missing-value indicator in this file is -9.9 for variable WIND.

First two data records:

```
 1993   1  8.04  3.61   66.8359   1.0   1.6   4.8  9.7  65.2  74.9  84.3  6.9
6.9  7.0 -9.9
 1993   2  8.04  3.61   66.8359   0.0   1.6   4.9  9.7  65.2  75.0  84.3  6.7
6.8  6.9 -9.9
```

Last two data records:

```
 2000 365  8.90  4.70   57.0000   0.0 -10.5  -8.2 -6.3  63.0  71.1  83.3  3.7
4.0  4.7  2.1
 2000 366 14.30  7.60   85.0000   0.0  -8.7  -6.3 -3.3  57.3  72.6  85.4  3.2
3.6  3.9  1.4
```

Table 12 describes the format and contents of the ASCII data files **hw9399.dat (File 13)** and **hw00.dat (File 14)** distributed with this numeric data package.

Table 12. Contents and format of hw9399.dat (File 13) and hw00.dat (File 14)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
MOY	Integer	3	6	8	month	Month of the year (1 = January, ..., 12 = December)
DOY	Integer	4	9	12	d	Day of the year (1 = 1 January, ..., 365 or 366 = 31 December)
DFOY	Real	7	13	19	d	Day fraction of the year
HOY	Integer	5	20	24	h	Hour of the year
QUAN	Integer	5	25	29	Fmol m^{-2} s^{-1}	Mean incident photosynthetically active radiation (PAR)
PYRAN	Integer	5	30	34	W m^{-2}	Mean incident hourly radiation
UQUAN	Integer	5	35	39	Fmol m^{-2} s^{-1}	Mean hourly understory (1.5 m above ground level) PAR
AT	Real	6	40	45	deg C	Hourly mean air temperature
RH	Real	6	46	51	%	Hourly mean relative humidity
RAIN	Real	5	52	56	mm	Hourly rainfall
WIND	Real	5	57	61	m/s	Mean hourly wind speed
ST	Real	5	62	66	deg C	Mean 1-h soil temperature (10- to 15-cm depth)
VPD	Real	7	67	73	kPa	Mean vapor pressure deficit

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
SWISIS	Integer	5	74	78	W m^{-2}	Mean incident shortwave radiation

The missing-value indicators in file **hw9399.dat** are -99 for variables QUAN, UQUAN, and SWISIS; -9.9 for variables WIND and ST; -99.9 for variable AT; and -9.999 for variable VPD.

First two data records in file **hw9399.dat**:

```
1993  1   1   1.00    0    0    0  -99   2.6  71.2  0.0 -9.9  7.0  0.213  -99
1993  1   1   1.04    1    0    0  -99   2.4  71.8  0.0  2.6  7.0  0.206  -99
```

Last two data records in file **hw9399.dat**:

```
1999 12 365 365.96 8759    0    0    0  11.2  65.9  0.0  2.5  9.7  0.454    0
1999 12 365 366.00 8760    0    0    0  11.4  64.6  0.0  2.5  9.8  0.454    0
```

There are no missing values in file **hw00.dat**.

First two data records in file **hw00.dat**:

```
2000  1   1   1.04    1    0    0    0  11.1  66.1  0.0  2.3  9.4  0.449    0
2000  1   1   1.08    2    0    0    0  10.4  69.0  0.0  2.1  9.3  0.392    0
```

Last two data records in file **hw00.dat**:

```
2000 12 366 366.96 8783    0    0    0  -5.6  70.3  0.0  1.6  3.6  0.120    0
2000 12 366 367.00 8784    0    0    0  -5.9  73.8  0.0  1.7  3.6  0.104    0
```

Table 13 describes the format and contents of the ASCII data file **comptree.dat (File 15)** distributed with this numeric data package.

Table 13. Contents and format of comptree.dat (File 15)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
ID	Real	7	1	7	n/a	Arbitrary individual tree identification number
SPC	Character	8	8	15	n/a	Species code (see listing of codes and species names in Appendix C)
TREAT	Character	2	16	17	n/a	Treatment (W = wet, A = ambient, D = dry)
SLOPE	Character	2	18	19	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	3	20	22	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	23	25	arbitrary units	X coordinate position across the slope
YM	Real	5	26	30	m	Y coordinate position up/down the slope
XM	Real	6	31	36	m	X coordinate position across the slope
D010693	Real	6	37	42	cm	Diameter at height = 1.3 m on 1 June 1993
D010694	Real	6	43	48	cm	Diameter at height = 1.3 m on 1 June 1994
D011294	Real	6	49	54	cm	Diameter at height = 1.3 m on 1 December 1994

Table 13 (continued)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
D010695	Real	6	55	60	cm	Diameter at height = 1.3 m on 1 June 1995
D010796	Real	6	61	66	cm	Diameter at height = 1.3 m on 1 July 1996
D010797	Real	6	67	72	cm	Diameter at height = 1.3 m on 1 July 1997
D010998	Real	6	73	78	cm	Diameter at height = 1.3 m on 1 September 1998
D011299	Real	6	79	84	cm	Diameter at height = 1.3 m on 1 December 1999
D290101	Real	6	85	90	cm	Diameter at height = 1.3 m on 29 January 2001

Trees that died during the experiment are represented as missing in the years after death occurred. Trees that reached (or approached) the 10 cm dbh cutoff during the experiment are represented as missing until the year they attained tree status.

The missing-value indicator in this file is -99.9 for variables D010693, D010694, D011294, D010695, D010796, D010797, D010998, D011299, and D290101.

First two data records:

```
   30.0AR      W U   8  2 61.6  11.9 -99.9 -99.9   9.9   9.9  10.9  11.4  12.1
12.7  13.5
   32.0AR      A B   2 16 15.1 122.5 -99.9 -99.9  10.4  10.4  11.5  12.3  12.9
13.1  13.7
```

Last two data records:

```
 6019.0CF      D B   1 24  2.5 189.6 -99.9 -99.9 -99.9 -99.9   9.8  10.1  11.3
10.3  10.4
 6020.0OA      D B   1 23  0.8 182.4 -99.9 -99.9 -99.9 -99.9  12.1  12.2  12.5
12.8  12.9
```

Table 14 describes the format and contents of the ASCII data file **compsap.dat (File 16)** distributed with this numeric data package.

Table 14. Contents and format of compsap.dat (File 16)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
ORDER	Real	6	1	6	n/a	Arbitrary individual tree identifier
SPC	Character	9	7	15	n/a	Species code (see listing of codes and species names in Appendix C)
TREAT	Character	2	16	17	n/a	Treatment (W = wet, A = ambient,D = dry)
SLOPE	Character	2	18	19	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	2	20	21	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	22	24	arbitrary units	X coordinate position across the slope
PLOTID	Integer	3	25	27	n/a	Number of the sapling within an individual plot
D1996	Real	6	28	33	cm	Diameter at height = 1.3 m in year 1996
D1997	Real	6	34	39	cm	Diameter at height = 1.3 m in year 1997
D1998	Real	6	40	45	cm	Diameter at height = 1.3 m in year 1998
D1999	Real	6	46	51	cm	Diameter at height = 1.3 m in year 1999

The missing-value indicators in this file are -9.99 for variables D1996, D1997, D1998, and D1999.

First two data records:

```
   1.0AR       W U  9  2  1  2.12  2.32 -9.99 -9.99
   2.0AR       W U  9  2  2  2.96  2.95 -9.99 -9.99
```

Last two data records:

```
 597.0QV       D B  3 27 13  4.17  4.18  4.40  4.44
 598.0Carya    D B  3 27 14  1.52  1.50  1.60  1.61
```

Table 15 describes the format and contents of the ASCII data file **atree.dat (File 17)** distributed with this numeric data package.

Table 15. Contents and format of atree.dat (File 17)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
ID	Integer	5	6	10	n/a	Arbitrary individual tree identification number
SPC	Character	3	11	13	n/a	Species code (see listing of codes and species names in Appendix C)
TREAT	Character	2	14	15	n/a	Treatment (W = wet, A = ambient, D = dry)
SLOPE	Character	2	16	17	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	3	18	20	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	21	23	arbitrary units	X coordinate position across the slope
GROWTH	Integer	6	24	29	mm^2/y	Basal area growth rate

The missing-value indicator in this file is -9999 for variable GROWTH.

First two data records:

```
 1993   51AR A M   5 12  2673
 1993   52AR A M   5 12  2462
```

Last two data records:

```
 2000 2992QA A M   6 13  1576
 2000 2996QP W M   5  9  2157
```

Table 16 describes the format and contents of the ASCII data file **asapling.dat (File 18)** distributed with this numeric data package.

Table 16. Contents and format of asapling.dat (File 18)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	4	1	4	y	Year
ID	Character	8	5	12	n/a	Arbitrary individual tree identification number
SPC	Character	3	13	15	n/a	Species code (see listing of codes and species names in Appendix C)
TREAT	Character	2	16	17	n/a	Treatment (W = wet, A = ambient, D = dry)
SLOPE	Character	2	18	19	n/a	Slope position (U = upper, M = middle, B = bottom)
Y	Integer	3	20	22	arbitrary units	Y coordinate position up/down the slope
X	Integer	3	23	25	arbitrary units	X coordinate position across the slope
GROWTH	Real	7	26	32	mm^2/y	Basal area growth rate

The missing-value indicator in this file is -9.999 for variable GROWTH.

First two data records:

```
1994 3001   AR W U  10  1  0.122
1994 3002   AR A U  10 11  0.090
```

Last two data records:

```
2000 4027a  CF A M   6 14 -9.999
2000 5015a  CF W B   3  8 -9.999
```

Table 17 describes the format and contents of the ASCII data file **rellai.dat (File 19)** distributed with this numeric data package.

Table 17. Contents and format of rellai.dat (File 19)

Variable	Variable type	Variable width	Starting column	Ending column	Units	Definition and comments
YEAR	Integer	5	1	5	y	Year
DOY	Integer	4	6	9	d	Day of the year (1 = 1 January, ..., 365 = 31 December)
RELLAI	Real	6	10	15	n/a	Fractional LAI (leaf area index)

The missing-value indicator in this file is -9.99 for variable RELLAI.

First two data records:

```
 1992  85 -9.99
 1992  86 -9.99
```

Last two data records:

```
 2000 349 -9.99
 2000 350 -9.99
```

10. SAS® AND FORTRAN CODES TO ACCESS THE DATA

The following is SAS® code to read file **sw.dat**:

```
/*** retrieval routine to read sw.dat ***/

data sw ;

infile '/home/cdp/ndp078a/sw.dat' ;
input DATE $ 1-18 RDOY 19-23 DOY 24-27 W35WC 28-32 A35WC 33-37 D35WC 38-42
      W35WP 43-48 A35WP 49-54 D35WP 55-60 W70WC 61-65 A70WC 66-70 D70WC 71-75
      W3570WC 76-80 A3570WC 81-85 D3570WC 86-90 W3570WP 91-96 A3570WP 97-102
      D3570WP 103-108 ;

run ;
```

The following is Fortran code to read file **sw.dat**:

```
C *** Fortran program to read the NDP-078a file "sw.dat"
C
      INTEGER RDOY, DOY
      REAL W35WC, A35WC, D35WC, W35WP, A35WP, D35WP, W70WC,
     +     A70WC, D70WC, W3570WC, A3570WC, D3570WC, W3570WP,
     +     A3570WP, D3570WP
      CHARACTER DATE*18
C
      OPEN (UNIT=1, FILE='sw.dat')
C
   10 READ (1,100,END=99) DATE, RDOY, DOY, W35WC, A35WC, D35WC,
     + W35WP, A35WP, D35WP, W70WD, A70WC, D70WC, W3570WC, A3570WC,
     + D3570WC, W3570WP, A3570WP, D3570WP
  100 FORMAT (A18,I5,I4,3F5.1,3F6.2,6F5.1,3F6.2)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **nine.dat**:

```
/*** retrieval routine to read nine.dat ***/

data nine ;

infile '/home/cdp/ndp078a/nine.dat' ;
input YEAR 1-5 DOY 6-9 RDOY 10-14 WBWC 15-19 WMWC 20-24 WUWC 25-29
      ABWC 30-34 AMWC 35-39 AUWC 40-44 DBWC 45-49 DMWC 50-54 DUWC 55-59
      WBWP 60-66 WMWP 67-73 WUWP 74-80 ABWP 81-87 AMWP 88-94
      AUWP 95-101 DBWP 102-108 DMWP 109-115 DUWP 116-122 ;

run ;
```

The following is Fortran code to read file **nine.dat**:

```
C *** Fortran program to read the NDP-078a file "nine.dat"
C
      INTEGER YEAR, DOY, RDOY
      REAL WBWC, WMWC, WUWC, ABWC, AUWC, DBWC, DMWC, DUWC,
     +     WBWP, WMWP, WUWP, ABWP, AMWP, AUWP, DBWP, EMWP,
     +     DUWP
C
      OPEN (UNIT=1, FILE='nine.dat')
C
   10 READ (1,100,END=99) YEAR, DOY, RDOY, WBWC, WMWC, WUWC,
     + ABWC, AMWC, AUWC, DBWC, DMWC, DUWC, WBWP, WMWP, WUWP,
     + ABWP, AMWP, AUWP, DBWP, DMWP, DUWP
  100 FORMAT (I5,I4,I5,9F5.1,9F7.3)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **tdr.dat**:

```
/*** retrieval routine to read tdr.dat ***/

data tdr ;

infile '/home/cdp/ndp078a/tdr.dat' ;
input YEAR 1-5 DOY 6-9 DEPTH 10-12 TREAT $ 13-14 SLOPE $ 15-16 Y 17-19
      X 20-22 YM 23-25 XM 26-29 SWC 30-34 ;

run ;
```

The following is Fortran code to read file **tdr.dat**:

```
C *** Fortran program to read the NDP-078a file "tdr.dat"
C
      INTEGER YEAR, DOY, DEPTH, Y, X, YM, XM
      REAL SWC
      CHARACTER TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='tdr.test')
C
   10 READ (1,100,END=99) YEAR, DOY, DEPTH, TREAT, SLOPE,
     + Y, X, YM, XM, SWC
  100 FORMAT (I5,I4,I3,2A2,3I3,I4,F5.1)
C
```

```
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS$^{®}$ code to read file **rocks.dat**:

```
/*** retrieval routine to read rocks.dat ***/

data rocks ;

infile '/home/cdp/ndp078a/rocks.dat' ;
input TREAT $ 1-2 SLOPE $ 3-4 Y 5-7 X 8-10
      CFMASS30 11-15 CFVOL30 16-21 CFPCT30 22-26
      CFMASS60 27-31 CFVOL60 32-37 CFPCT60 38-42 ;

run ;
```

The following is Fortran code to read file **rocks.dat**:

```
C *** Fortran program to read the NDP-078a file "rocks.dat"
C
      INTEGER Y, X, CFMASS30, CFMASS60
      REAL CFVOL30, CFPCT30, CFVOL60, CFPCT60
      CHARACTER TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='rocks.dat')
C
   10 READ (1,100,END=99) TREAT, SLOPE, Y, X, CFMASS30,
     + CFVOL30, CFPCT30, CFMASS60, CFVOL60, CFPCT60
  100 FORMAT (2A2,2I3,2(I5,F6.1,F5.1))
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS$^{®}$ code to read file **littert.dat**:

```
/*** retrieval routine to read littert.dat ***/

data littert ;

infile '/home/cdp/ndp078a/littert.dat' ;
input YEAR 1-5 DOY 6-9 DFOY 10-16 TREAT $ 17-18 LITTERT 19-24  ;
```

```
run ;
```

The following is Fortran code to read file **littert.dat**:

```
C *** Fortran program to read the NDP-078a file "littert.dat"
C
      INTEGER YEAR, DOY
      REAL DFOY
      CHARACTER TREAT*2
C
      OPEN (UNIT=1, FILE='littert.dat')
C
   10 READ (1,100,END=99) YEAR, DOY, DFOY, TREAT, LITTERT
  100 FORMAT (I5,I4,F7.2,A2,F6.1)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **st9398.dat**:

```
*** retrieval routine to read st9398.dat ***/

data st9398 ;

infile '/home/cdp/ndp078a/st9398.dat' ;
input YEAR 1-5 MOY 6-8 DOY 9-12 DFOY 13-19 HOY 20-24
      ST10 25-30 ST35 31-36  ;

run ;
```

The following is Fortran code to read file **st9398.dat**:

```
C *** Fortran program to read the NDP-078a file "st9398.dat"
C
      INTEGER YEAR, MOY, DOY, HOY
      REAL DFOY, ST10, ST35
C
      OPEN (UNIT=1, FILE='st9398.dat')
C
   10 READ (1,100,END=99) YEAR, MOY, DOY, DFOY, HOY, ST10, ST35
  100 FORMAT (I5,I3,I4,F7.2,I5,2F6.1)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **st9900.dat**:

```
/*** retrieval routine to read st9900.dat ***/

data st9900 ;

infile '/home/cdp/ndp078a/st9900.dat' ;
input YEAR 1-5 MOY 6-8 DOY 9-12 DFOY 13-19 HOY 20-24
      ST10 25-32 ST27 33-40 STW6 41-46 STW31 47-52
      STW55 53-58 STW72 59-64 STA7 65-70 STA32 71-76
      STA59 77-82 STA100 83-88 STD9 89-94 STD30 95-100
      STD45 101-106 STD63 107-112 ;

run ;
```

The following is Fortran code to read file **st9900.dat**:

```
C *** Fortran program to read the NDP-078a file "st9900.dat"
C
      INTEGER YEAR, MOY, DOY, HOY
      REAL DFOY, ST10, ST27, STW6, STW31, STW55, STW72,
     + STA7, STA32, STA59, STA100, STD9, STD30, STD45, STD63
C
      OPEN (UNIT=1, FILE='st9900.dat')
C
   10 READ (1,100,END=99) YEAR, MOY, DOY, DFOY, HOY, ST10, ST27,
     + STW6, STW31, STW55, STW72, STA7, STA32, STA59, STA100,
     + STD9, STD30, STD45, STD63
  100 FORMAT (I5,I3,I4,F7.2,I5,2F8.4,12F6.2)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **mweather.dat**:

```
/*** retrieval routine to read mweather.dat ***/

data mweather ;

infile '/home/cdp/ndp078a/mweather.dat' ;
input YEAR 1-5 MONTH 6-8 QUAN 9-13 PYRAN 14-17 RAIN 18-21
      ATMIN 22-27 ATMEAN 28-32 ATMAX 33-37 RHMIN 38-42
      RHMEAN 43-47 RHMAX 48-53 STMIN 54-58 STMEAN 59-63
      STMAX 64-68 WIND 69-74;
```

```
run ;
```

The following is Fortran code to read file **mweather.dat**:

```
C *** Fortran program to read the NDP-078a file "mweather.dat"
C
      INTEGER YEAR, MONTH, QUAN, PYRAN, RAIN
      REAL ATMIN, ATMEAN, ATMAX, RHMIN, RHMEAN, RHMAX,
     + STMIN, STMEAN, STMAX, WIND
C
      OPEN (UNIT=1, FILE='mweather.dat')
C
   10 READ (1,100,END=99) YEAR, MONTH, QUAN, PYRAN, RAIN,
     + ATMIN, ATMEAN, ATMAX, RHMIN, RHMEAN, RHMAX, STMIN,
     + STMEAN, STMAX, WIND
  100 FORMAT (I5,I3,I5,2I4,F6.1,4F5.1,F6.1,3F5.1,F6.2)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **dweather.dat**:

```
/*** retrieval routine to read dweather.dat ***/

data dweather ;

infile '/home/cdp/ndp078a/dweather.dat' ;
input YEAR 1-5 DOY 6-9 QUAN 10-15 PYRAN 16-21 RADMEAN 22-31
      RAIN 32-37 ATMIN 38-43 ATMEAN 44-49 ATMAX 50-54 RHMIN 55-60
      RHMEAN 61-66 RHMAX 67-72 STMIN 73-77 STMEAN 78-82
      STMAX 83-87 WIND 88-92 ;

run ;
```

The following is Fortran code to read file **dweather.dat**:

```
C *** Fortran program to read the NDP-078a file "dweather.dat"
C
      INTEGER YEAR, DOY, RAIN
      REAL QUAN, PYRAN, RADMEAN, ATMIN, ATMEAN, ATMAX, RHMIN,
     + RHMEAN, RHMAX, STMIN, STMEAN, STMAX, WIND
C
      OPEN (UNIT=1, FILE='dweather.dat')
C
   10 READ (1,100,END=99) YEAR, DOY, QUAN, PYRAN, RADMEAN,
     + RAIN, ATMIN, ATMEAN, ATMAX, RHMIN, RHMEAN, RHMAX, STMIN,
     + STMEAN, STMAX, WIND
  100 FORMAT (I5,I4,2F6.2,F10.4,3F6.1,F5.1,3F6.1,4F5.1)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **hw9399.dat**:

```
/*** retrieval routine to read hw9399.dat ***/

data  hw9399 ;

infile '/home/cdp/ndp078a/hw9399.dat' ;
input YEAR 1-5 MOY 6-8 DOY 9-12 DFOY 13-19 HOY 20-24
      QUAN 25-29 PYRAN 30-34 UQUAN 35-39 AT 40-45
      RH 46-51 RAIN 52-56 WIND 57-61 ST 62-66
      VPD 67-73 SWISIS 74-78;

run ;
```

The following is Fortran code to read file **hw9399.dat**:

```
C *** Fortran program to read the NDP-078a file "hw9399.dat"
C
      INTEGER YEAR, MOY, DOY, HOY, QUAN, PYRAN, UQUAN, SWISIS
      REAL DFOY, AT, RH, RAIN, WIND, ST, VPD
C
      OPEN (UNIT=1, FILE='hw9399.dat')
C
   10 READ (1,100,END=99) YEAR, MOY, DOY, DFOY, HOY, QUAN,
     + PYRAN, UQUAN, AT, RH, RAIN, WIND, ST, VPD, SWISIS
  100 FORMAT (I5,I3,I4,F7.2,4I5,2F6.1,3F5.1,F7.3,I5)
C
```

```
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **hw00.dat**:

```
/*** retrieval routine to read hw00.dat ***/

data  hw00 ;

infile '/home/cdp/ndp078a/hw00.dat' ;
input YEAR 1-5 MOY 6-8 DOY 9-12 DFOY 13-19 HOY 20-24
      QUAN 25-29 PYRAN 30-34 UQUAN 35-39 AT 40-45
      RH 46-51 RAIN 52-56 WIND 57-61 ST 62-66
      VPD 67-73 SWISIS 74-78;

run ;
```

The following is Fortran code to read file **hw00.dat**:

```
C *** Fortran program to read the NDP-078a file "hw00.dat"
C
      INTEGER YEAR, MOY, DOY, HOY, QUAN, PYRAN, UQUAN, SWISIS
      REAL DFOY, AT, RH, RAIN, WIND, ST, VPD
C
      OPEN (UNIT=1, FILE='hw00.dat')
C
   10 READ (1,100,END=99) YEAR, MOY, DOY, DFOY, HOY, QUAN,
     + PYRAN, UQUAN, AT, RH, RAIN, WIND, ST, VPD, SWISIS
  100 FORMAT (I5,I3,I4,F7.2,4I5,2F6.1,3F5.1,F7.3,I5)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **comptree.dat**:

```
/*** retrieval routine to read comptree.dat ***/

data  comptree ;

infile '/home/cdp/ndp078a/comptree.dat' ;
input ID 1-7 SPC $ 8-15 TREAT $ 16-17 SLOPE $ 18-19 Y 20-22 X 23-25
```

```
      YM 26-30 XM 31-36 D010693 37-42 D010694 43-48 D011294 49-54
      D010695 55-60 D010796 61-66 D010797 67-72 D010998 73-78
      D011299 79-84 D290101 85-90 ;

run ;
```

The following is Fortran code to read file **comptree.dat**:

```
C *** Fortran program to read the NDP-078a file "comptree.dat"
C
      INTEGER Y, X
      REAL ID, YM, XM, D010693, D010694, D011294, D010695,
     + D010796, D010797, D010998, D011299, D290101
      CHARACTER SPC*8, TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='comptree.dat')
C
   10 READ (1,100,END=99) ID, SPC, TREAT, SLOPE, Y, X, YM,
     + XM, D010693, D010694, D011294, D010695, D010796,
     + D010797, D010998, D011299, D290101
  100 FORMAT (F7.1,A8,2A2,2I3,F5.1,10F6.1)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **compsap.dat**:

```
/*** retrieval routine to read compsap.dat ***/

data  compsap ;

infile '/home/cdp/ndp078a/compsap.dat' ;
input ORDER 1-6 SPC $ 7-15 TREAT $ 16-17 SLOPE $ 18-19 Y 20-21 X 22-24
      PLOTID 25-27 D1996 28-33 D1997 34-39 D1998 40-45 D1999 46-51 ;

run ;
```

The following is Fortran code to read file **compsap.dat**:

```
C *** Fortran program to read the NDP-078a file "compsap.dat"
C
      INTEGER ORDER, Y, X, PLOTID
      REAL D1996, D1997, D1998, D1999
      CHARACTER SPC*9, TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='compsap.dat')
C
   10 READ (1,100,END=99) ORDER, SPC, TREAT, SLOPE, Y, X,
     + PLOTID, D1996, D1997, D1998, D1999
  100 FORMAT (F6.1,A9,2A2,I2,2I3,4F6.2)
C
```

```
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **atree.dat**:

```
/*** retrieval routine to read atree.dat ***/

data  atree ;

infile '/home/cdp/ndp078a/atree.dat' ;
input YEAR 1-5 ID 6-10 SPC $ 11-13 TREAT $ 14-15 SLOPE $ 16-17 Y 18-20 X 21-23
      GROWTH 24-29 ;

run ;
```

The following is Fortran code to read file **atree.dat**:

```
C *** Fortran program to read the NDP-078a file "atree.dat"
C
      INTEGER YEAR, ID, Y, X, GROWTH
      CHARACTER SPC*3, TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='atree.dat')
C
   10 READ (1,100,END=99) YEAR, ID, SPC, TREAT, SLOPE,
     + Y, X, GROWTH
  100 FORMAT (2I5,A3,2A2,2I3,I6)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **asapling.dat**:

```
/*** retrieval routine to read asapling.dat ***/

data  asapling ;

infile '/home/cdp/ndp078a/asapling.dat' ;
input YEAR 1-4 ID $5-12 SPC $ 13-15 TREAT $ 16-17 SLOPE $ 18-19 Y 20-22
      X 23-25 GROWTH 26-32 ;
```

```
run ;
```

The following is Fortran code to read file **asapling.dat**:

```
C *** Fortran program to read the NDP-078a file "asapling.dat"
C
      INTEGER YEAR, Y, X
      REAL GROWTH
      CHARACTER ID*7, SPC*3, TREAT*2, SLOPE*2
C
      OPEN (UNIT=1, FILE='asapling.dat')
C
   10 READ (1,100,END=99) YEAR, ID, SPC, TREAT, SLOPE,
     + Y, X, GROWTH
  100 FORMAT (I4,A8,A3,2A2,2I3,F7.3)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

The following is SAS® code to read file **rellai.dat**:

```
/*** retrieval routine to read rellai.dat ***/

data  rellai ;

infile '/home/cdp/ndp078a/rellai.dat' ;
input YEAR 1-5 DOY 6-9 RELLAI 10-15 ;

run ;
```

The following is Fortran code to read file **rellai.dat**:

```
C *** Fortran program to read the NDP-078a file "rellai.dat"
C
      INTEGER YEAR, DOY
      REAL RELLAI
C
      OPEN (UNIT=1, FILE='rellai.dat')
C
   10 READ (1,100,END=99) YEAR, DOY, RELLAI
  100 FORMAT (I5,I4,F6.2)
C
      GO TO 10
   99 CLOSE (UNIT=1)
      STOP
      END
```

APPENDIX A: REPRINT OF PERTINENT LITERATURE

Hanson, P. J., D. E. Todd, M. A. Huston, J. D. Joslin, J. L. Croker, and R. M. Augé. 1998. *Description and field performance of the Walker Branch Throughfall Displacement Experiment: 1993-1996*. ORNL/TM-13586. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Because of copyright restrictions, this pdf file does not include the following two reprints:

Hanson, P. J., D. E. Todd, and J. S. Amthor. 2001. A six-year study of sapling and large-tree growth and mortality responses to natural and induced variability in precipitation and throughfall. *Tree Physiology* 21:345-358.

Joslin, J. D., M. H. Wolfe, and P. J. Hanson. 2000. Effects of altered water regimes on forest root systems. *New Phytologist* 147:117-129.

ORNL/TM-13586

Environmental Sciences Division

DESCRIPTION AND FIELD PERFORMANCE OF THE WALKER BRANCH THROUGHFALL DISPLACEMENT EXPERIMENT: 1993–1996

P. J. Hanson, D. E. Todd, M. A. Huston
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6422

J. D. Joslin
Tennessee Valley Authority
Norris, Tennessee 37828

J. L. Croker and R. M. Augé
Institute of Agriculture
University of Tennessee
Knoxville, Tennessee 37901

Environmental Sciences Division
Publication No. 4753

Date Published: April 1998

Prepared for the
Office of Biological and Environmental Research
U.S. Department of Energy
Under budget and reporting code KP1203010

PREPARED BY
OAK RIDGE NATIONAL LABORATORY
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
Under contract DE-AC05-96OR22464

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table **Page**

ABSTRACT

Hanson, P. J., D. E. Todd, M. A. Huston, J. D. Joslin, J. L. Croker, and R. M. Augé. 1998. Description and field performance of the Walker Branch Throughfall Displacement Experiment: 1993–1996. ORNL/TM-13586. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

We are conducting a large-scale (19,200-m^2) manipulative field experiment in an upland oak forest on the Walker Branch Watershed in eastern Tennessee to identify important ecosystem responses that might result from future precipitation changes. The manipulation of soil water content is being implemented by a gravity-driven transfer of throughfall from one 6400-m^2 treatment plot to another. Throughfall is intercepted in ≈1850 subcanopy troughs (0.3 × 5 m) suspended above the forest floor of the 'dry' plot (≈33% of the ground area is covered) and transferred by gravity flow across an ambient plot for subsequent distribution onto the 'wet' treatment plot. Soil water content is being monitored at two depths (0 to 0.35 and 0.35 to 0.7 m) with time domain reflectometers at 310 sampling locations across the site. The experimental system is able to produce statistically significant differences in soil water content in years having both dry and wet conditions. Maximum soil water content differentials between wet and dry plots in the 0- to 0.35-m soil horizon were 8 to 10% during summers with abundant precipitation and 3 to 5% during drought periods. Treatment impacts on soil water potential were restricted to the surface soil layer. Comparisons of pre- and post-installation soil and litter temperature measurements showed the ability of the experimental design to produce changes in soil water content and water potential without creating large artifacts in the forest understory environment.

ACKNOWLEDGMENTS

The authors thank James Arnett, Nelson Edwards, Howard Marotto, Michael Hayes, Kristin Harter, Todd Tabberer, Tracy Misek, Benjamin Stringfellow, and Stan Wullschleger for their valuable assistance in the collection of the field data. We also acknowledge the contributions of Stan Wullschleger, Jeff Amthor, and several anonymous ad hoc reviewers for providing comments on an early version of this paper. The research was sponsored by the Program for Ecosystem Research within the U.S. Department of Energy's Environmental Sciences Division, Office of Biological and Environmental Research. The research was conducted on the Oak Ridge National Environmental Research Park.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) concluded that climate changed over the past century, that human activities have had an influence on these changes, and that climate is expected to continue to change in the future (Houghton et al. 1996). Depending on the emission scenarios assumed, continued increases in the levels of greenhouse gases in the atmosphere are expected to induce an additional 1 to 3.5°C increase in average global surface temperatures by the year 2100 (Kattenburg et al. 1996). These temperature increases are expected to modify global hydrologic budgets, leading to increased winter precipitation at high latitudes, more hot days and fewer cold days, and more or fewer droughts or floods, depending on location (Kattenburg et al. 1996; Rind et al. 1990). These predicted changes in climate have raised concerns about potential impacts on terrestrial ecosystem productivity, biogeochemical cycling, and the availability of water resources (Kirschbaum and Fischlin 1996; Melillo et al. 1990, 1996).

The responses of forests to decreased water availability or increased occurrence of drought is currently considered a key issue in climate change scenarios (Wigley et al. 1984). Nielson et al. (1989) concluded that forests throughout the United States could experience severe impacts from climate change, especially in the southern states, where potential evapotranspiration is predicted to increase the most (Smith and Tirpak 1989). Concerns regarding vegetation impacts have been amplified because rates of change are expected to occur much faster than past successional processes and species dispersal rates (Davis 1989; Overpeck et al. 1991; Pastor and Post 1988; Solomon 1986). The actual directions and magnitude of expected changes in precipitation are highly uncertain, and specific scenarios for regional climate change are only preliminary (Cooter et al. 1993; Mohnen and Wang 1992; Rind et al. 1992; Schneider 1989).

Controlled experiments in greenhouses and growth chambers provide us with a large database of information concerning the impacts of moisture manipulations on the physiology and growth of forest tree seedlings and saplings (e.g., Ellsworth and Reich 1992; Hinckley et al. 1978; Kleiner et al. 1992; Kolb et al. 1990; Pezeshki and Chambers 1986), but concerns remain as to the appropriateness of the extrapolation of such data to mature tree responses in forest stands, where our understanding is limited largely to short-term responses to water stress (Cregg et al. 1989; Hinckley et al. 1978) or to a limited number of trees (Dougherty and Hinckley 1981; Epron et al. 1992; Ginter-Whitehouse et al. 1983). Manipulative field experiments can play a role in the identification of important ecosystem responses that might result from future precipitation changes.

Recent review articles (Graham et al. 1990; Mooney 1991; Mooney et al. 1991; Woodward 1992) have called for large-scale manipulation experiments to adequately address the impacts of changing climates on ecosystems. This paper describes the Walker Branch Throughfall Displacement Experiment (TDE) and evaluates its field performance from 1993 through 1996. The TDE is a 19,200-m^2 field manipulation experiment developed for mechanistic studies of the adaptation and acclimation of organisms to changing precipitation conditions. The goal of the TDE experiment is to develop a mechanistic understanding of how forest ecosystem organisms adjust to changes in precipitation inputs. Preliminary discussions of the TDE and its performance can also be found in papers by Turner et al. (1993) and Hanson et al. (1995).

2. TDE DESCRIPTION AND METHODS

2.1 SITE DESCRIPTION

The TDE is 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 mean annual precipitation is 1358 mm (Table 1), and mean temperature is 14.1 °C (Table 2). The acidic forest soils (pH 3.5 to 4.6) are primarily Typic Paleudults. These ancient residual soils are cherty silt loams that are infertile and highly permeable. They formed over a dolomitic bedrock but retain little evidence of their carbonate parent material. Depth to bedrock at this location is approximately 30 m. The past 25 years of research on the Walker Branch Watershed (Johnson and Van Hook 1989) provide an important reference database against which to judge the outcomes of the our large-scale manipulation.

The TDE experimental site was chosen because of its uniform slope, consistent soils, and a reasonably uniform distribution of vegetation. The experimental area was located at the upper divide of the watershed so that lateral flow of water into the soils at the top of the treatment area would not confound attempts to create the modified soil water treatments. The site was chosen to have a southern aspect so that the impacts of the reduced moisture treatment would be increased under greater net radiation levels.

2.2 EXPERIMENTAL DESIGN

The manipulations of throughfall reaching the forest floor are made with a system designed to transfer precipitation passively from one experimental plot to another (Fig. 1). One advantage of our passive design is that all modifications of ambient throughfall are conducted in real time so that they are coordinated with appropriate atmospheric conditions (i.e., artificial rainfall is not added under high-light–low-humidity conditions). Throughfall precipitation is intercepted in ~1850 subcanopy troughs suspended above the forest floor of the 'dry' plots (~33% of the ground area in the dry plot is covered in this 6400-m^2 plot). The throughfall is then transferred by gravity flow across an ambient plot (6400 m^2) and distributed onto the 'wet' treatment plot (6400 m^2) through paired drip holes spaced approximately 1 m apart. The troughs are arranged in 21 rows of ~90 troughs. Although stemflow is expected to contribute as much as 10% of the precipitation reaching the forest floor in heavy rain events, depending on species, tree size, season and storm dynamics, collection and transfer of stem flow were not included in the current design (Ragsdale et al. 1992).

The individual throughfall collection troughs (0.3 × 5 m) are made of 6-mil greenhouse-grade polyethylene, and they are installed at variable angles, depending on their position on the slope. The lower and upper ends of each trough are approximately 1.5 and 2.5 m off of the ground, respectively. The average ground area covered by each trough is less than each trough's total area because of their sloped installation.

The polyethylene troughs are supported on a frame of ~20-mm galvanized electrical metallic conduit and attached with large (~25.4-mm) binder clips (Charles Leonard Inc., Glendale, New York). Standard aluminum gutters (~150 mm wide) positioned directly below the trough outlets collected the throughfall from a series of troughs. The troughs and gutters were constructed in 12.2-m modular sections so that damaged (wind and/or fallen large branches) sections would not compromise throughfall interception and transfer of an entire collection line. Water collected in each modular trough/gutter assembly was drained via a reinforced flexible hose into a continuous 160-m pipeline made of ~100-mm schedule 40 PVC. This pipeline served as the storage container and transfer pipeline for the collected throughfall. The distribution pipeline laid out across the wet plot was constructed of ~50-mm schedule 40 PVC pipe.

Table 1. Amounts of precipitation at the Throughfall Displacement Experiment: (A) Monthly measurements, annual totals, and long-term means, and (B) Measurements or estimates for the ambient, wet treatment, and dry treatment plots during the growing season (i.e., May through September)

Parameter	Year					Mean for 1949–1996
	1992	1993	1994	1995	1996	
	A. Monthly ambient plot precipitation (mm)					
January	86	101	142	135	171	129
February	83	50	249	97	37	118
March	96	173	254	94	147	143
April	42	105	226	64	103	104
May	58	68	59	175	177	110
June	102	15	194	55	178	104
July	130	81	128	47	259	132
August	86	93	106	15	68	96
September	79	126	82	102	101	94
October	67	50	64	128	40	76
November	144	95	98	132	214	114
December	147	182	73	92	143	140
Annual total	1118	1139	1675	1135	1638	1358
	B. Growing-season precipitation (mm)					
Ambient plot	454	383	569	394	783	534
Wet plot	—	—	~759	~525	~1044	—
Dry plot	—	—	~379	~263	~522	—

Table 2. Temperatures and cumulative amounts of radiation at the Throughfall Displacement Experiment and Walker Branch Watershed: (A) Mean monthly, growing-season (leaf-out to leaf-off), and annual temperatures and (B) cumulative monthly, growing-season, and annual radiation

Parameter	Throughfall Displacement Experiment					Walker Branch Watershed
	1992	1993	1994	1995	1996	1951–1996
A. Mean temperatures (°C)						
January	4.0	5.6	–0.2	3.4	1.8	2.5
February	7.1	3.7	5.9	4.0	4.0	4.5
March	8.6	7.5	8.6	11.8	6.6	8.9
April	14.7	12.8	15.4	16.0	13.1	14.3
May	17.6	19.6	16.5	19.1	20.5	18.9
June	21.9	23.7	23.8	22.4	23.0	23.0
July	25.2	27.8	24.8	25.5	23.7	24.9
August	22.9	25.9	24.0	25.7	23.6	24.4
September	21.6	22.1	19.7	20.6	19.5	21.0
October	14.1	15.4	15.6	14.7	14.8	14.6
November	8.3	7.9	11.4	6.2	6.5	8.5
December	3.8	4.2	7.1	3.1	5.7	4.1
Growing season	18.3	19.7	20.0	19.3	19.5	NA[a]
Annual	14.2	14.8	14.4	14.4	13.6	14.1
B. Cumulative radiation (MJ m^{-2})						
January	NA[a]	186	158	192	145	NA[a]
February	NA[a]	241	254	246	234	NA[a]
March	NA[a]	281	373	465	402	NA[a]
April	574	476	518	545	503	NA[a]
May	550	580	635	526	624	NA[a]
June	537	612	550	587	622	NA[a]
July	559	656	517	654	556	NA[a]
August	484	548	483	551	572	NA[a]
September	399	434	459	398	404	NA[a]
October	308	320	360	365	378	NA[a]
November	191	215	268	218	207	NA[a]
December	131	174	163	212	177	NA[a]
Growing season	3403	3570	3497	3658	3488	NA[a]
Annual	NA[a]	4724	4737	4960	4824	NA[a]

[a] NA = not available.

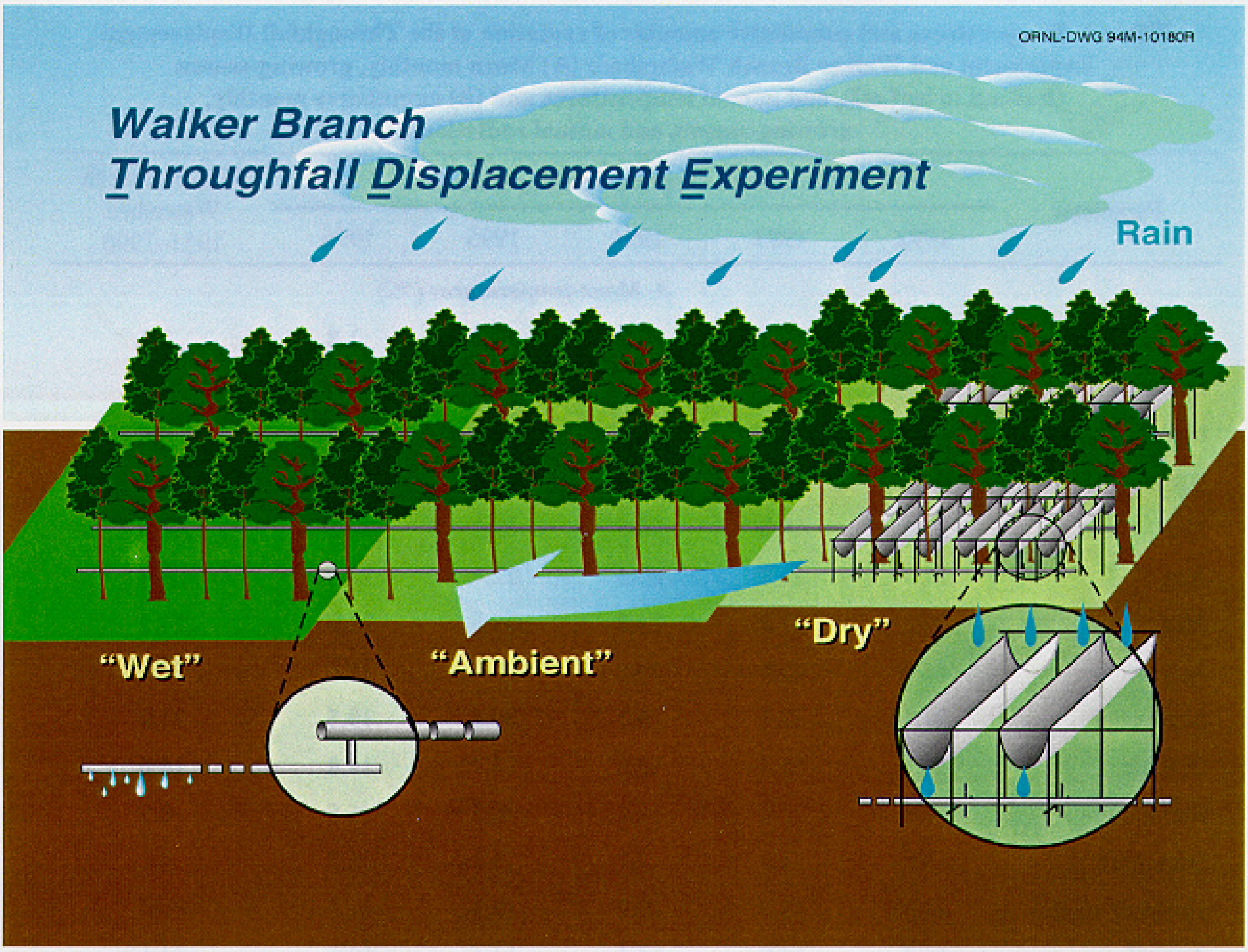


Fig. 1. Schematic diagram of the trough and piping network responsible for transporting ≈33% of total throughfall from the dry experimental plot across the ambient plot to distribution pipes extending the width of the wet plot. Each treatment plot was divided into an upper (rows 7–10), middle (rows 4–6), and lower (rows 1–3) slope position to account for elevational effects.

Paired lengths of iron concrete reinforcing bar (12.5 mm) of variable lengths were hammered vertically into the ground below the frost line, and short lengths of conduit were installed horizontally between the two pieces of reinforcing bar to form 'H-frames' on which the collection and distribution pipelines were supported and adjusted for appropriate drainage.

To ensure that mature trees of each plot had their canopies and root systems fully contained within a given soil water condition, the experimental plots were made as large as possible. Each treatment plot is 80 by 80 m (size was limited by the amount of uniform space available along the slope) and divided into 100 subplots that serve as the locations for repetitive, nondestructive measurements of soil and plant characteristics. Soil water content was chosen as the primary measurement for documenting ambient plot vs wet and dry treatment plot differences. Daily to weekly visual inspections of the trough and gutters and occasional measurements of the flow rates from each of the 20 pipelines were conducted to ensure uniform throughfall interception by the troughs.

The experimental design was not replicated because of cost and logistical limitations. Lack of replication forces a reliance on "pseudoreplication" (Eberhardt and Thomas 1991). Addressing pseudoreplication in our sampling design is critical (Hurlbert 1984). Eberhardt and Thomas (1991) recommend that unreplicated experiments be supported by adequate sampling of site environmental parameters (including climatic conditions), comparable ambient areas, and pretreatment sampling of key variables. To provide information for those variables, the site topography, soils, soil water patterns, microclimate, and vegetation were extensively characterized before setting up the throughfall displacement system. Although not without limitations, unreplicated experimental designs have been used to provide invaluable understanding of forest ecosystem processes in large-scale manipulative studies at the watershed scale. Classic examples are the Hubbard Brook (Borman and Likens 1979) and Coweeta watershed studies (Swank and Crossley 1988).

2.3 VEGETATION CHARACTERISTICS

Prior to beginning the experiment, all individual plants greater than 0.1 m in diameter at 1.3 m (diameter at breast height; dbh) were identified by species (729 individual trees), and tree heights and canopy widths were measured directly or derived from allometric relationships. An aerial view of the distribution of these species across the TDE is shown in Fig. 2. In addition, a side view of the vertical position of each species in the canopy is shown by slope position in Fig. 3. Figures 2 and 3 show the dominance of *Quercus* sp. with *Acer* sp. as a key co-dominant. *Liriodendron tulipifera* L. occurs as a canopy dominant on the lower slope positions, and *Nyssa sylvatica* Marsh. and *Oxydendrum arboreum* [L.] D.C. are predominant species occupying mid-canopy locations. Stand basal area averaged 21 m^2 ha^{-1} across the TDE, with nearly identical basal area on each treatment plot (Table 3). The number of saplings (trees < 0.1 m dbh) across the TDE area averages 3073 ha^{-1} and contributes an additional 3.3 m^2 ha^{-1} to total stand basal area (Table 4). *Acer rubrum* L. and *Cornus florida* L. make up 59% of all saplings and 48% of the sapling basal area.

2.4 SOIL WATER MEASUREMENTS

The percentage soil water content was measured with a time domain reflectometer (TDR; 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 et al. 1987). To verify that TDR would yield soil water content data consistent with past data based on gravimetric observations on Walker Branch (Peters et al. 1970), we conducted cross comparison tests in 1993. The linear relationship, shown in Fig. 4 with a slope near 1, indicates general agreement between TDR-based soil water content measurements and gravimetric measurements of soil water content. Variability around this curve results from the coarse fraction of our soils (10 to 20%) and the paired but not identical placement of the TDR probes and the destructive samples used for gravimetric water content determinations.

Sampling locations for TDR measurements were laid out in an 8 × 8 m grid across the TDE for a total of 310 sampling locations. Two pairs of TDR waveguides were installed at each of the grid intersections. Each pair was positioned vertically from the surface. The shallow pair extended from the surface to 0.35 m, and the deep pair extended from the surface to 0.7 m. The shallow depth (i.e., 0 to 0.35 m) corresponded to the zone of maximum root density on our site (Wolfe et al. 1997), and the 0.7 m depth neared the recommended maximum length for our TDR. Shallow soil water measurements in the 0- to 0.15-m depth were initially collected. However, they were discontinued because permanent 0- to 0.15-m rod installations were too susceptible to damage by random foot traffic. Point-in-time measurements with a single set of 0.15-m rods attached to the waveguide connector were possible only for wet soils. Installation of horizontal buriable probes was not pursued in order to minimize disturbance to the forest floor.

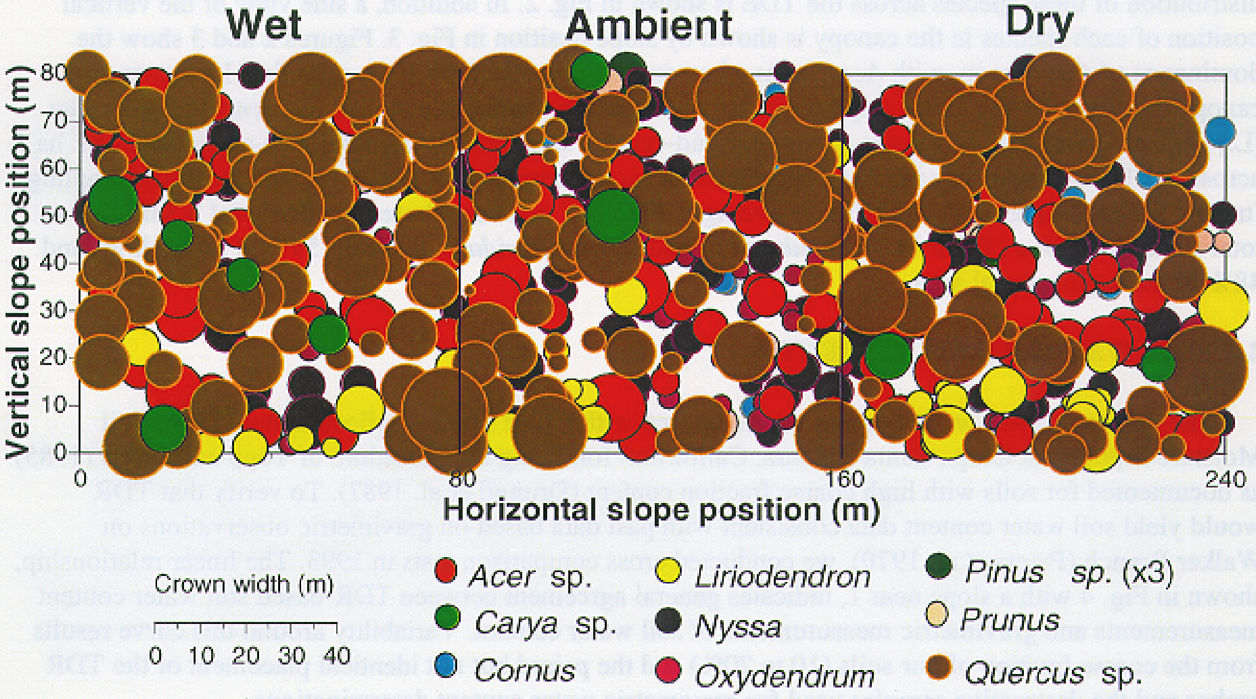


Fig. 2. An aerial view of the horizontal species distribution of all trees greater than 0.1 m in diameter at dbh across the Throughfall Displacement Experiment as of 1996. Circle size represents the canopy width of each tree. Top of the figure represents the top of the slope.

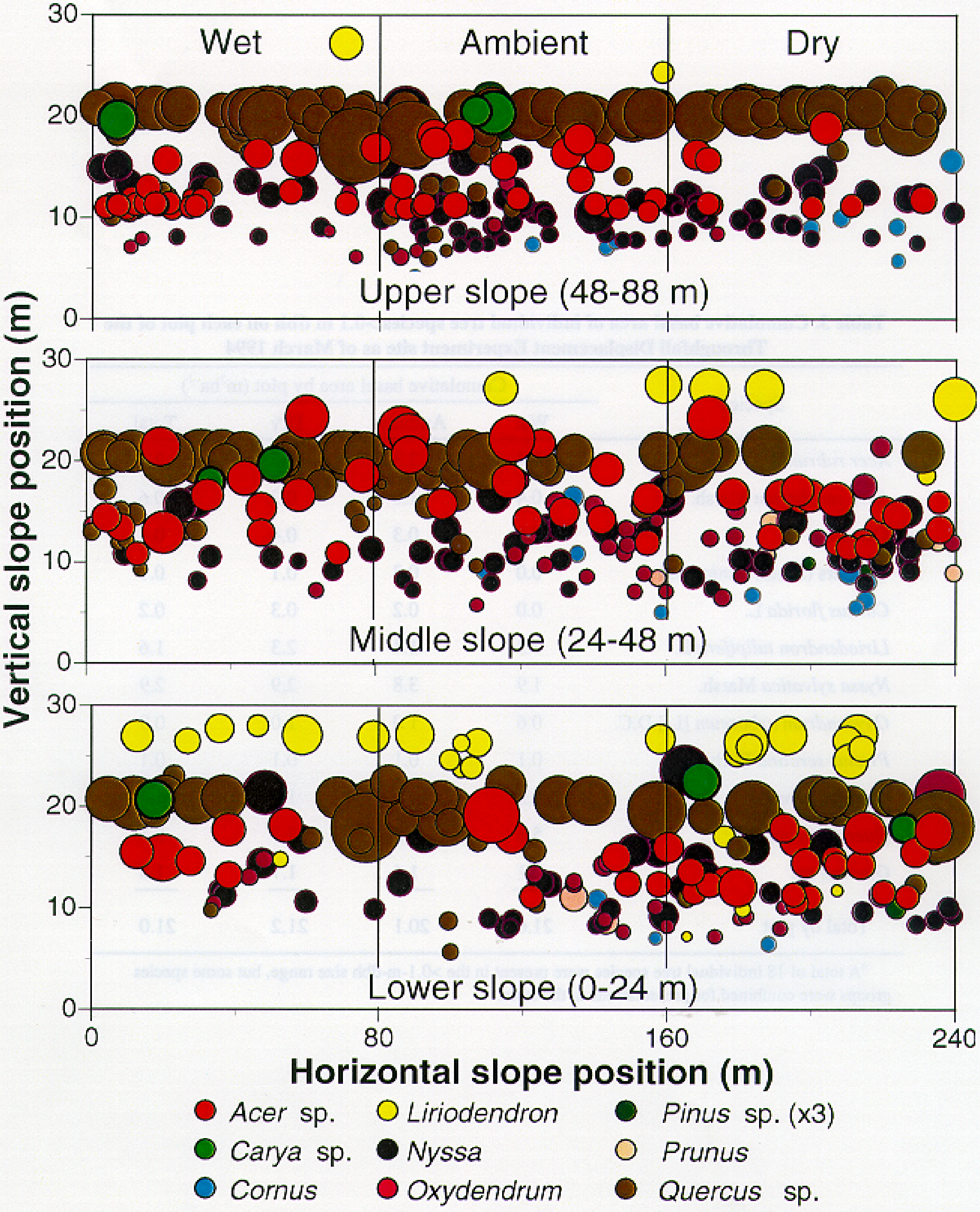


Fig. 3. A side view of the vertical position of individual tree crowns for (A) upper, (B) middle, and (C) lower slope positions across the Throughfall Displacement Experiment. Circle size represents the canopy width of each tree. Because this figure is based on trees greater than 0.1 m dbh few crowns are shown below a height of ~6 m.

Table 3. Cumulative basal area of individual tree species >0.1 m dbh on each plot of the Throughfall Displacement Experiment site as of March 1994

Species[a]	Cumulative basal area by plot (m^2ha^{-1})			
	Wet	Ambient	Dry	Total
Acer rubrum L.	2.4	2.3	2.5	2.4
Acer saccharum Marsh.	0.4	1.0	0.3	0.6
Carya sp.	0.6	0.3	0.4	0.4
Conifers (*Pinus, Juniperus*)	0.0	0.3	0.1	0.1
Cornus florida L.	0.0	0.2	0.3	0.2
Liriodendron tulipifera L.	1.3	1.4	2.3	1.6
Nyssa sylvatica Marsh.	1.9	3.8	2.9	2.9
Oxydendrum arboreum [L.] D.C.	0.6	1.0	1.0	0.9
Prunus serotina Ehrh.	0.1	0.1	0.1	0.1
Quercus alba L.	6.5	4.9	1.9	4.4
Quercus prinus L.	5.6	3.3	7.7	5.5
Quercus sp.	2.1	1.4	1.7	1.8
Total by plot	21.6	20.1	21.2	21.0

[a] A total of 18 individual tree species were present in the >0.1-m-dbh size range, but some species groups were combined for presentations in the table.

Table 4. Number of individuals and cumulative basal area of each sapling species <0.1 m dbh on each plot of the Throughfall Displacement Experiment site

Species	Cumulative Basal area by plot (m^2ha^{-1})			
	Wet	Ambient	Dry	Total
	Number of saplings ha^{-1}			
Acer rubrum L.	1649	1215	1181	1348
Acer saccharum Marsh.	0	87	17	35
Carya sp.	191	104	87	127
Cornus florida L.	174	764	434	457
Fagus grandifolia J. F. Ehrh.	69	104	69	81
Nyssa sylvatica Marsh.	0	365	122	162
Oxydendrum arboreum [L.] D.C.	69	122	122	104
Prunus serotina Ehrh.	35	0	191	75
Quercus sp.	139	243	208	197
Quercus alba L.	35	35	0	23
Quercus prinus L.	52	0	0	17
Rhamnus sp.	0	0	174	58
Sassafras albidum (Nutt.) Nees	17	69	17	35
Miscellaneous	469	504	87	353
Total	2899	3611	2708	3073
	Cumulative sapling basal area by species and plot (m^2ha^{-1})			
Acer rubrum L.	1.34	0.70	0.90	0.98
Acer saccharum Marsh.	0.00	0.02	0.10	0.06
Carya sp.	0.03	0.05	0.01	0.03
Cornus florida L.	0.27	0.81	0.78	0.62
Fagus grandifolia J. F. Ehrh.	0.03	0.04	0.03	0.03
Nyssa sylvatica Marsh.	0.00	0.68	0.26	0.47
Oxydendrum arboreum [L.] D.C.	0.33	0.21	0.24	0.26
Prunus serotina Ehrh.	0.01	0.00	0.30	0.15
Quercus sp.	0.16	0.22	0.10	0.16
Quercus alba L.	0.01	0.12	0.00	0.07
Quercus prinus L.	0.03	0.00	0.00	0.00
Rhamnus sp.	0.00	0.00	0.22	0.22
Sassafras albidum (Nutt.) Nees	0.03	0.14	0.01	0.06
Miscellaneous	0.28	0.34	0.09	0.24
Total	2.51	3.31	3.05	3.35

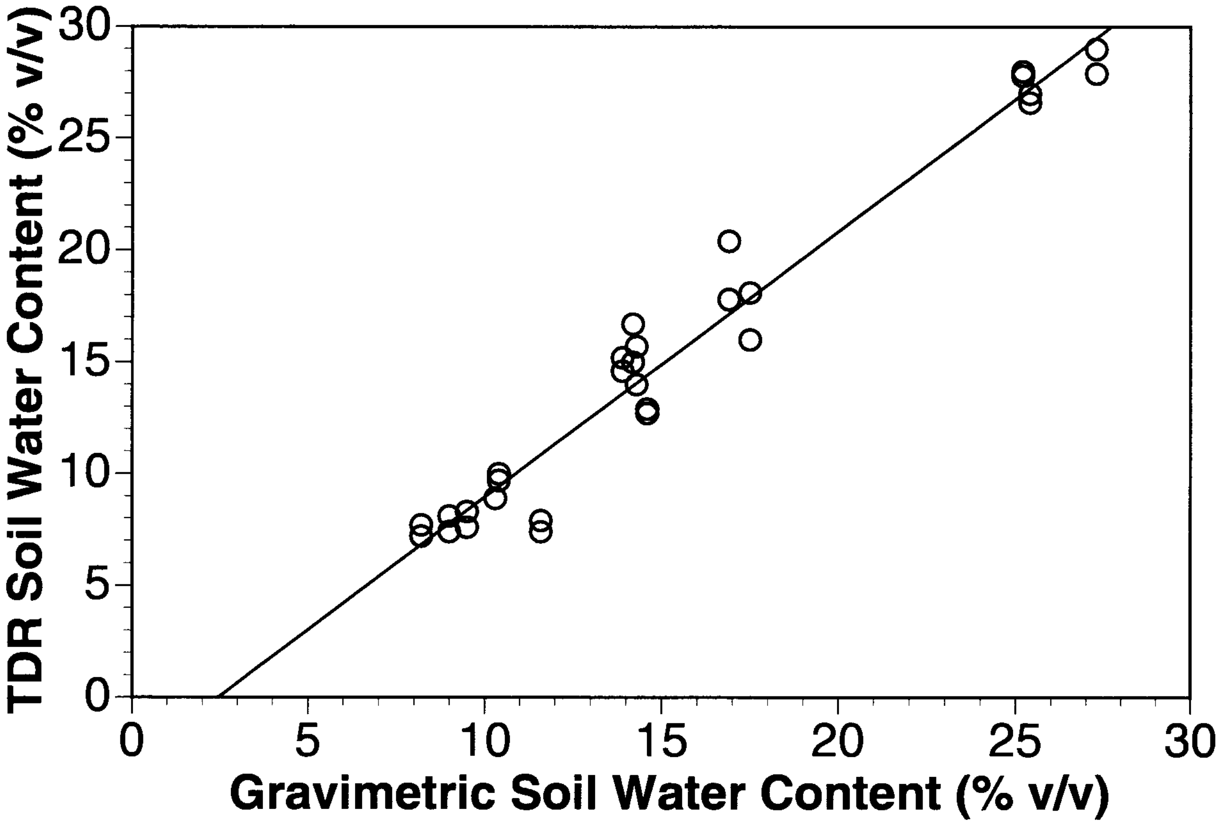


Fig. 4. Comparison of soil water content (v/v) obtained by means of time domain reflectometer and gravimetric approaches corrected for bulk density.

TDR waveguide installation was initiated in March 1992, but the complete complement of rods was not fully in place until August 12, 1992 (day 225). With all TDR rods installed, measurements of the water content across all sites were initiated (620 observations per measurement date). Soil water measurements were conducted biweekly during the growing season and monthly for dormant periods. Multiple TDR machines were required to accomplish the 620 observations on each measurement date (2 work days). On any given date, all measurements at a specific depth were made with the same machine. Intermachine comparisons conducted since 1992 indicate good agreement between TDR machines (data not shown).

Because the integrated measurement of the percent soil water in the 0- to 0.7-m depth interval (SW70) contains all of the soil water measured by the 0- to 0.35-m waveguides (SW35), the percent soil water content in the 0.35- to 0.7-m portion of the profile (SW3570) can be estimated by subtraction from the following equation:

$$SW_{3570} = \frac{[(SW_{70} * 0.7\,m^3) - (SW_{35} * 0.35\,m^3)]}{0.35\,m^3}\ , \tag{1}$$

where 0.7 and 0.35 m^3 are the total and partial volumes of a hypothetical soil sample 1 × 1 × (0.7 or 0.35) m.

2.5 SOIL WATER POTENTIAL ESTIMATES

Soil moisture retention curves were evaluated for representative A, AE, and EB horizon soils collected adjacent to the TDE site using psychrometric measurements of soil water potential and gravimetric measurements of soil water content (Fig. 5). Thermocouple psychrometers (SC-10, Decagon Devices, Inc., Pullman, Washington), calibrated before each use with a graded series of NaCl solutions, and nanovoltmeter thermometers (NT-3, Decagon Devices) were used to derive μV and temperature readings for conversion into water potential values.

The AE soil retention curve was assumed to be applicable to the 0- to 0.35-m soil depth increment, and that the EB soil retention curve was assumed appropriate for the 0.35- to 0.7-m depth. These assumptions are of course subject to some error because of variations in the thickness of soil horizons across the TDE. To convert raw volumetric water content data (TDR_r) collected on the TDE site-to-soil-water potential in MPa, TDR_r must first be corrected to account for the mean coarse fraction of the soil in question (Table 5). The appropriate calculation is as follows:

$$TDR_c = \frac{TDR_r}{\left(\frac{100}{C_f}\right)} * 100 \ , \tag{2}$$

where C_f is the appropriate mean coarse fraction for the TDE location of interest. Subsequent to this correction, TDR_c is used as an input to the equations in Fig. 5 to yield soil water potentials for the depth increment.

2.6 WEATHER CONDITIONS

Incoming rainfall, irradiance (Pyranometer sensor, LiCor Inc., Lincoln, Nebraska), photosynthetic photon flux density (Quantum sensor, LiCor, Inc.), air temperature, and relative humidity (Model MP-100 Rotronics Instrument Corporation, Huntington, New York) were measured continuously and logged as hourly means at a clearing close to the TDE site as a surrogate for "above-canopy" inputs. Understory climate data, including photosynthetically active radiation (PAR) at 1.5 m, air temperature, soil temperatures (0.1 and 0.35 m), and relative humidity, were also logged hourly on each treatment plot. Throughfall quantity on each experimental plot is also being monitored with two tipping bucket rain gauges with ≈3-m extension troughs attached. Air and soil temperature sensors (LiCor, Inc., Lincoln, Nebraska) used with the data loggers (LI-1000, LiCor, Inc., Lincoln, Nebraska) are thermistors set to read over a –10 to 50°C range.

To better judge the impact of the dry plot troughs on understory microclimates, additional litter and soil temperature measurements were conducted periodically from 1994 through 1996. These observations were conducted on four transects (1 upslope, 2 midslope, 1 downslope) across the treatment plots (31 observations per transect). Transect observations were made during the growing and dormant seasons to determine if the TDE infrastructure had a microclimatic effect that differed with the extent of leaf-out or canopy closure. Soil temperatures were collected with a penetrating thermocouple capable of recording to the nearest ±0.1 °C (Model 450-AET Omega Engineering Inc., Stamford, Connecticut). Forest floor litter surface temperatures were measured with an infrared thermometer (Everest Scientific, Inc., Fullerton, California), with the emissivity set to 0.98.

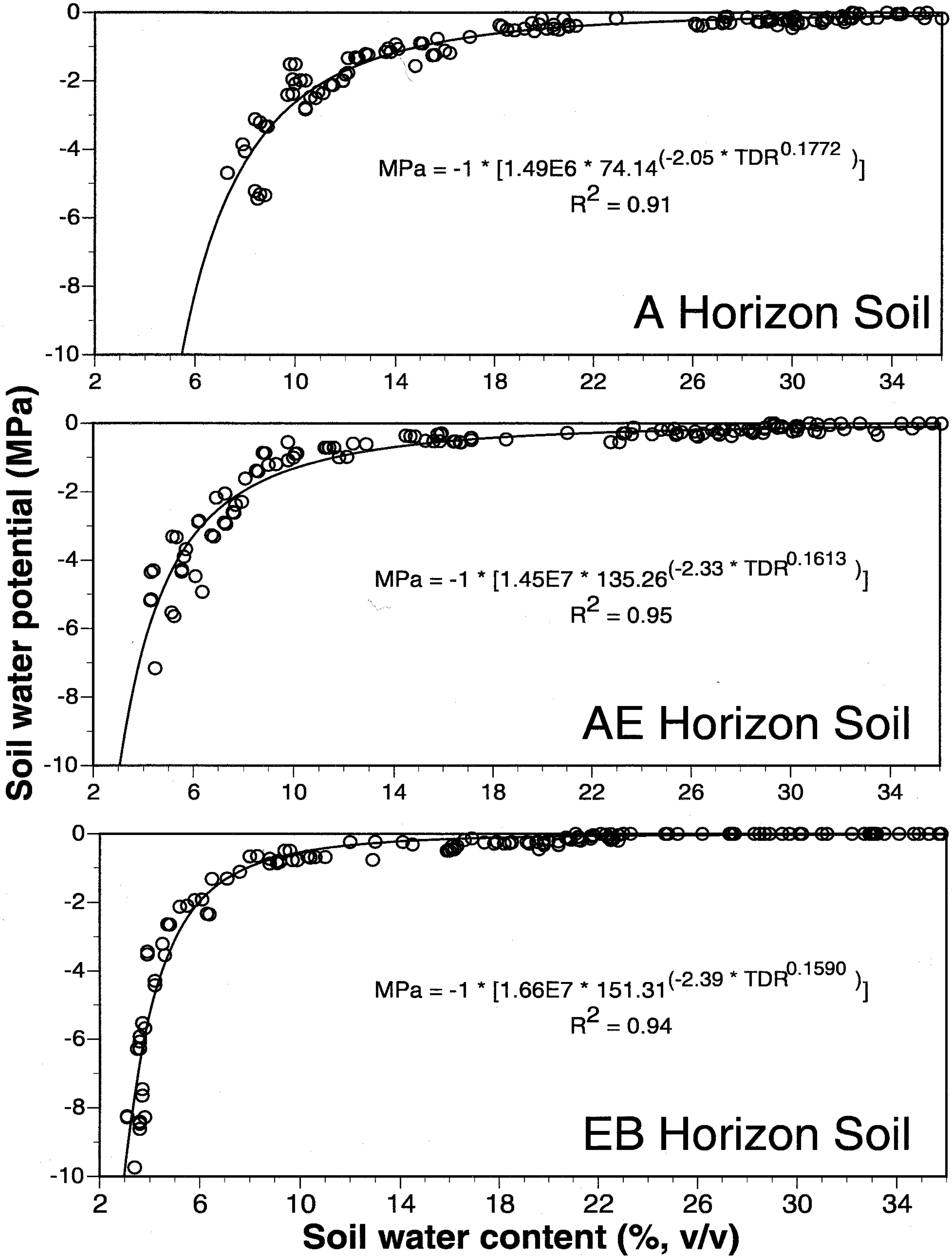


Fig. 5. Soil moisture release curves for representative A, AE, and EB horizon soils of the Throughfall Displacement Experiment. The fitted curves were generated with nonlinear least squares approaches.

Table 5. Coarse fraction volume percent by position and depth increment on the Throughfall Displacement Experiment (TDE) site[a]

TDE position	Coarse fraction (%) by depth	
	0–0.3 m	0.3–0.6 m
Wet plot	13.1	17.0
Up	14.4	17.1
Middle	12.5	18.1
Lower	11.5	15.1
Ambient plot	14.2	16.9
Up	15.9	17.3
Middle	13.0	16.6
Lower	12.7	16.2
Dry plot	15.3	17.2
Up	16.2	16.6
Middle	14.4	18.3
Lower	14.8	16.4
TDE site mean	14.2	17.0

[a] Volume percent was determined from the average mass of rock material greater than 2-mm diam sieved from ten 0.002432-m^3 cores of soil per TDE position. Average rock density was 2300 kg m^{-3}.

2.7 STATISTICAL APPROACH

Pretreatment measurements (April 1992 through July 12, 1993) of soil water content and within-date analysis of variance for pretreatment horizontal and vertical slope positions across the TDE indicated the existence of pretreatment gradients in water content across the TDE area. There was a decreasing gradient of soil water from the lower to the upper slope positions, and the mean soil water content of the eastern third of the plot was lower than the rest. To effectively judge the effectiveness of the throughfall transfer system, these spatial patterns needed to be captured in a covariate matrix that could describe the influence of a specific slope position with respect to the overall site mean soil water content.

The pretreatment observations of the TDR grid network, measured from August 1992 through July 12, 1993, were used to generate this covariate matrix. The covariate matrix of values was determined from the experimental area's mean soil water content and its relationship to the grand mean for all locations:

$$Y_{ij} = \Sigma(Y_{ijk})/n \quad \text{(in this study, } n = 11\text{)} \;, \tag{3}$$

$$Y = \Sigma(Y_{ij})/n \quad \text{(in this study, } n = 310\text{)} \;, \tag{4}$$

$$\mathrm{Cov}Y_{ij} = (Y_{ij} - Y)/\mathrm{sd}Y \;, \tag{5}$$

where Y_{ij} is the mean annual value for a given location, Y is the grand mean for all locations and times, *i* and *j* are the horizontal and vertical coordinates of the TDE experimental area, *k* is the month of the observation, and *n* is the number of observations for a given summation. A contour plot of the covariate ranks for each of the measurement locations across the TDE is shown in part B of Fig. 6. Positive and negative values represent locations that exhibit greater or lesser water contents than the grand mean, respectively. Note that the overall tendency is for the dry treatment area to already be drier than the ambient and wet plots prior to beginning the experiment. Slope position, soil texture, and coarse fraction may contribute to the observed pretreatment tendencies across the TDE area. Although we hoped that a single covariate rank based on an entire year's worth of data would be robust enough to apply to all subsequent dates, we ended up generating two covariate ranks: one for the dormant season when soil water conditions are near saturation and one for summer periods. These covariate ranks are not substantially different than the overall ranks shown in Fig. 6.

Before the covariate analysis of variance could be used to test for significant treatment effects on soil water contents across the TDE, a lack of spatial autocorrelation among the individual rod pairs needed to be demonstrated. Semivariograms (Turner et al. 1991) based on TDR measurements of soil water content at a 0.15-m spacing along both vertical and horizontal transects within the TDE area demonstrated that beyond 4 to 5 m the individual soil water measurements can be considered independent (data not shown). Therefore, having satisfied the need for independence of each measurement the individual soil water measurements at 8 by 8 m can be considered as true replicates. Covariate data sets were not available for litter and soil temperatures. A two-way analysis of variance was conducted to evaluate the impact of the trough and gutter infrastructure on understory microclimates. All statistical analyses were conducted with SPSS 6.1 for the Macintosh (SPSS, Inc., Chicago, Illinois).

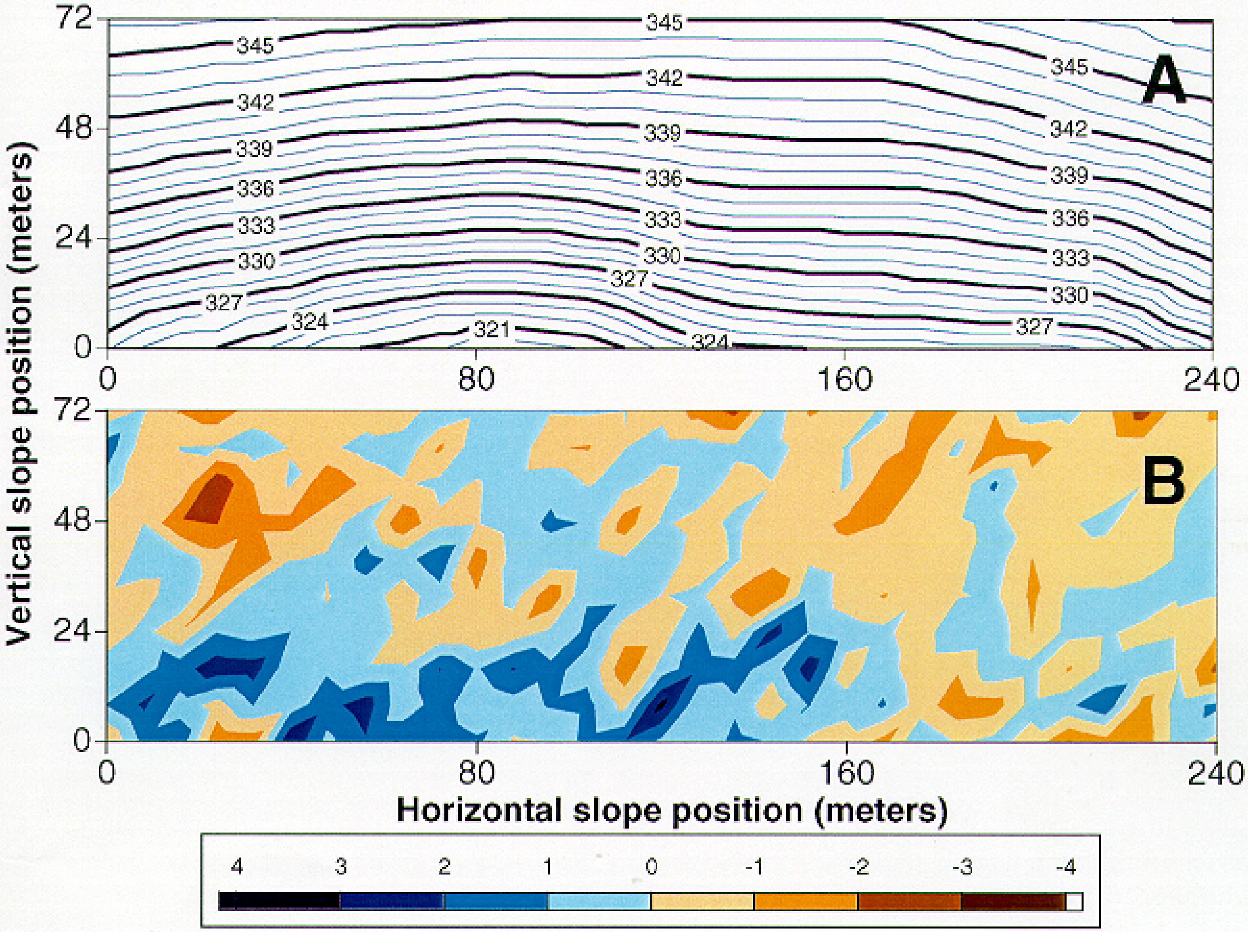


Fig. 6. (A) Elevation map of the experimental area in meters and (B) contour plot showing the pretreatment pattern of soil water across the experimental site expressed relative to the mean for the entire experimental area. A location with a rank of zero would be in agreement with the overall site mean.

3. TDE PERFORMANCE AND DISCUSSION

3.1 1993–1996 WEATHER

Climate and soil water measurements collected from 1992 through 1996 showed substantial variation in ambient precipitation conditions. The 1993 and 1995 seasons had ~16% lower annual precipitation and 24 to 27% lower growing season rainfall than the long-term average for Walker Branch Watershed (Table 1). Conversely, 1994 and 1996 had 21 to 23% higher-than-average total annual precipitation. Growing season precipitation was near normal for 1994, but 47% higher in 1996 (Table 1). Ambient temperatures and cumulative incident radiation were not as variable as precipitation from 1993 through 1996 (Table 2). The 1993 drought year had higher-than-average annual and growing season temperatures, and the wettest year (i.e., 1996) had the lowest mean annual temperature. Growing-season temperatures in 1994, 1995, and 1996 were nearer to normal (Table 2). Cumulative growing-season radiation inputs ranged from 2461 to 2830 MJ m^{-2} from 1992 through 1996 but showed no consistent trends with annual or growing-season precipitation. The variable interannual climate and precipitation regimes allowed us to conduct the TDE under conditions ranging from wet (1996) to dry (1993 and 1995). The closest year to the mean ambient year was 1994.

3.2 TDE IMPACTS ON VOLUMETRIC WATER CONTENT

The seasonal patterns of mean TDR soil water content by treatment in the 0- to 0.35- and 0.35- to 0.7-m depth increments from 1993 through 1996 are shown in Fig. 7. Since the initiation of treatments in 1993, significant differences in the soil water content in the 0- to 0.35-m depth increment have been present, except during dormant seasons when all soils were at or near saturation, or at the depth of the drought in 1995 (See Appendix Tables A1 through A9). During a typical winter rain event on February 11, 1994, a subset of the 0- to 0.35-m rods were measured under saturated conditions and we found the soils of the wet plot to be significantly elevated above those of the ambient and dry treatment areas (data not shown). Calculated soil water contents for the 0.35- to 0.7-m depth show a similar separation of treatment means, but the differences are not as great nor are they as sustained in any one season as those in the 0- to 0.35-m layer.

Contour plots of the 0- to 0.35-m soil water contents for selected dates in 1993, 1994, 1995, and 1996 are shown in Figs. 8 through 11, respectively. In each year of our study it is clear that we always begin the growing season with saturated soils. Subsequently, with the initiation of substantial evaporative demand and canopy transpiration in mid-to-late May the dry-plot water contents are drawn down faster than those in the ambient and wet plots. In the drought years of 1993 (Fig. 8) and 1995 (Fig. 10), long periods without rainfall cause treatment differentials to disappear. However, following the depth of droughts in 1993 and 1995 treatment differences redeveloped as the soils refilled. Substantial impacts on the dry-plot water budget were maintained well into November 1993 and 1994 (Figs. 8 and 9).

A decreasing gradient of soil water from the lower to the upper slope positions is evident across the TDE area. Lower slope positions typically maintain higher water contents caused by gravity drainage of water laterally through the soils (Mulholland 1993). The slope effect is not without exception. For example, some mid-slope locations have higher water contents than the lower-slope areas (e.g., mid-slope on the dry plot). Over the entire season it would appear that positional differences across the TDE site are maximal during dry periods and minimal in the dormant season when the system nears field capacity. The permanent site bias due to soil characteristics is captured in the covariate rankings described previously (Fig. 6). A careful comparison of the patterns of Fig. 6 and the soil water contour plots of Figs. 8 through 11 indicates the consistency of this pattern except under the driest conditions.

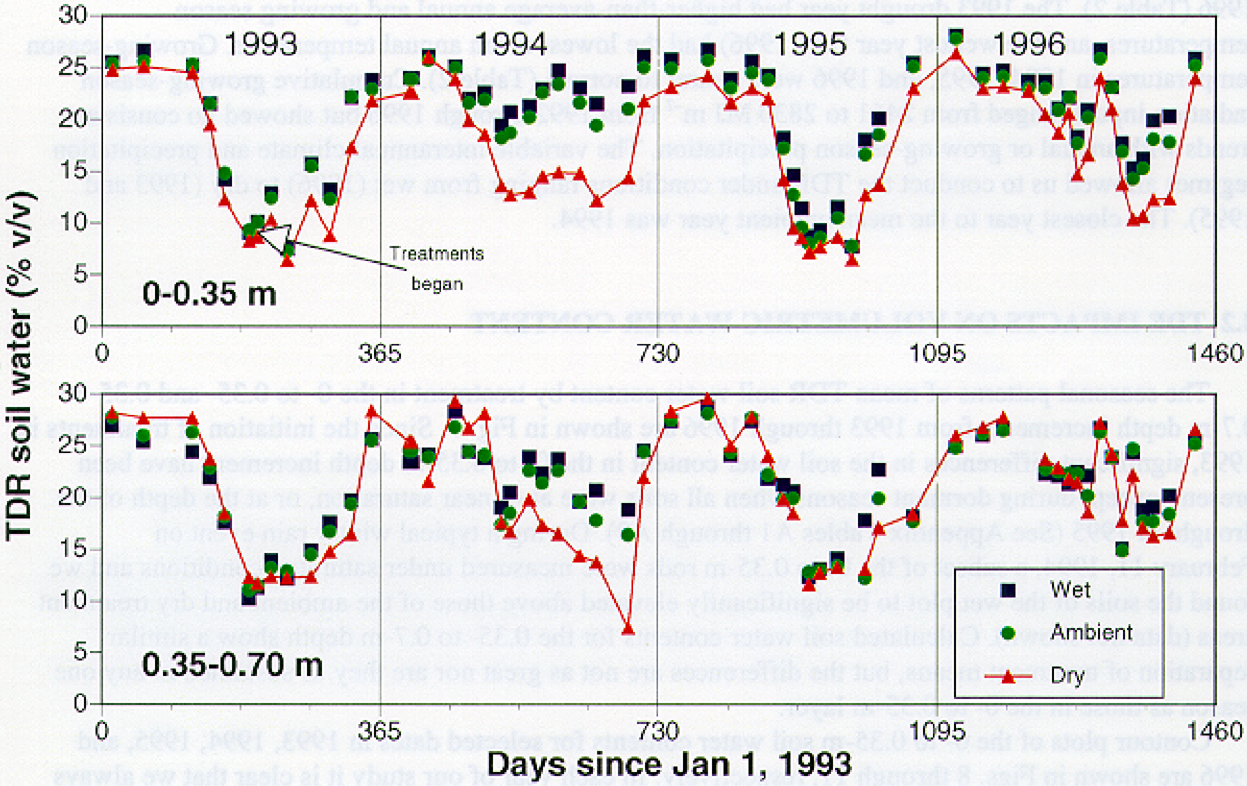


Fig. 7. The seasonal patterns of soil water content (% v/v) from 1993 through 1996 for the 0- to 0.35-m and the 0.35- to 0.7-m soil depths. Data are the mean values for the wet, ambient, and dry plots on the Walker Branch Throughfall Displacement Experiment. Throughfall displacement treatments were initiated on July 14, 1993 (see arrow at top left).

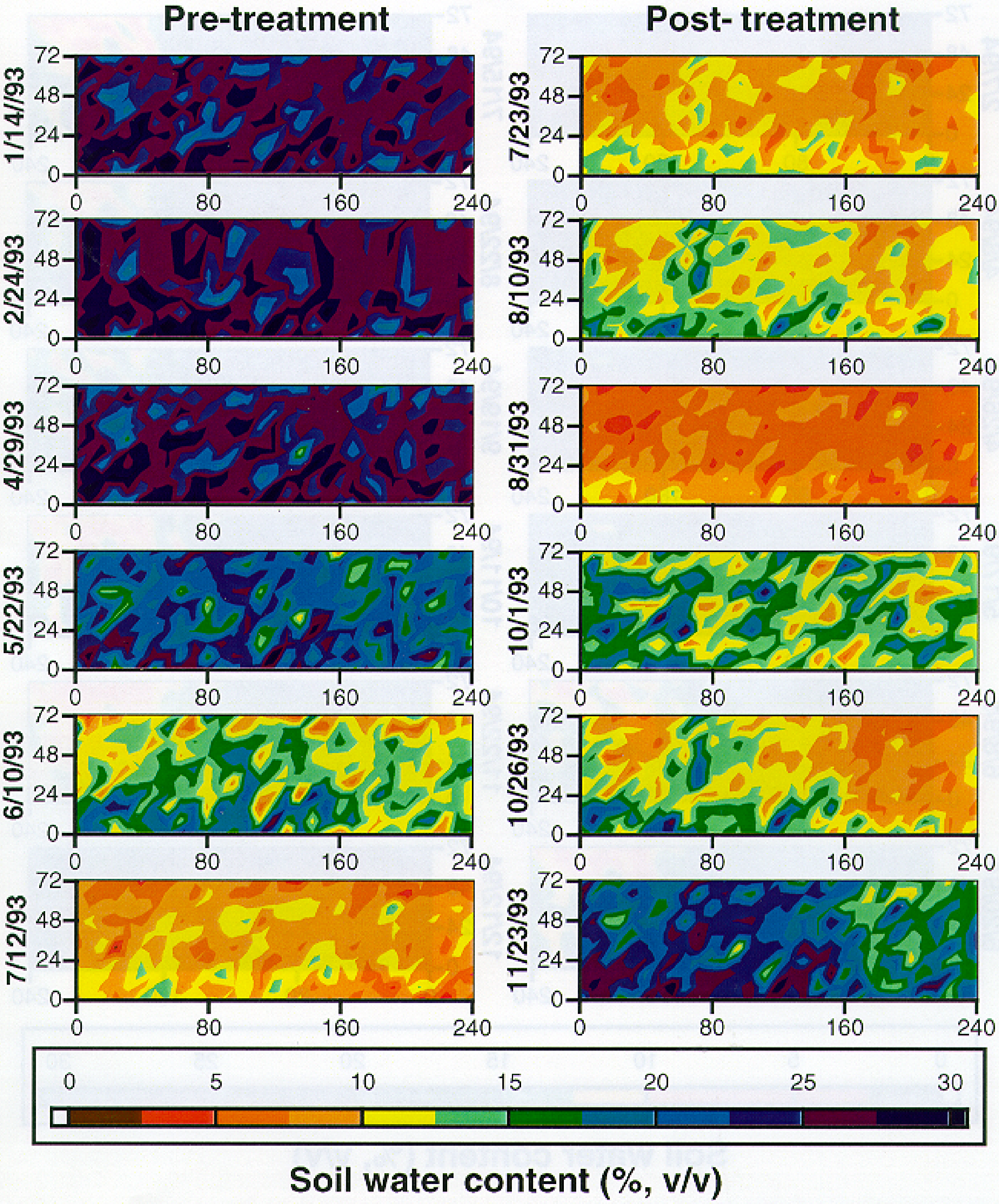


Fig. 8. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1993. Throughfall displacement was initiated between July 12 and July 23. Numbers along the x- and y-axis of each plot are meters.

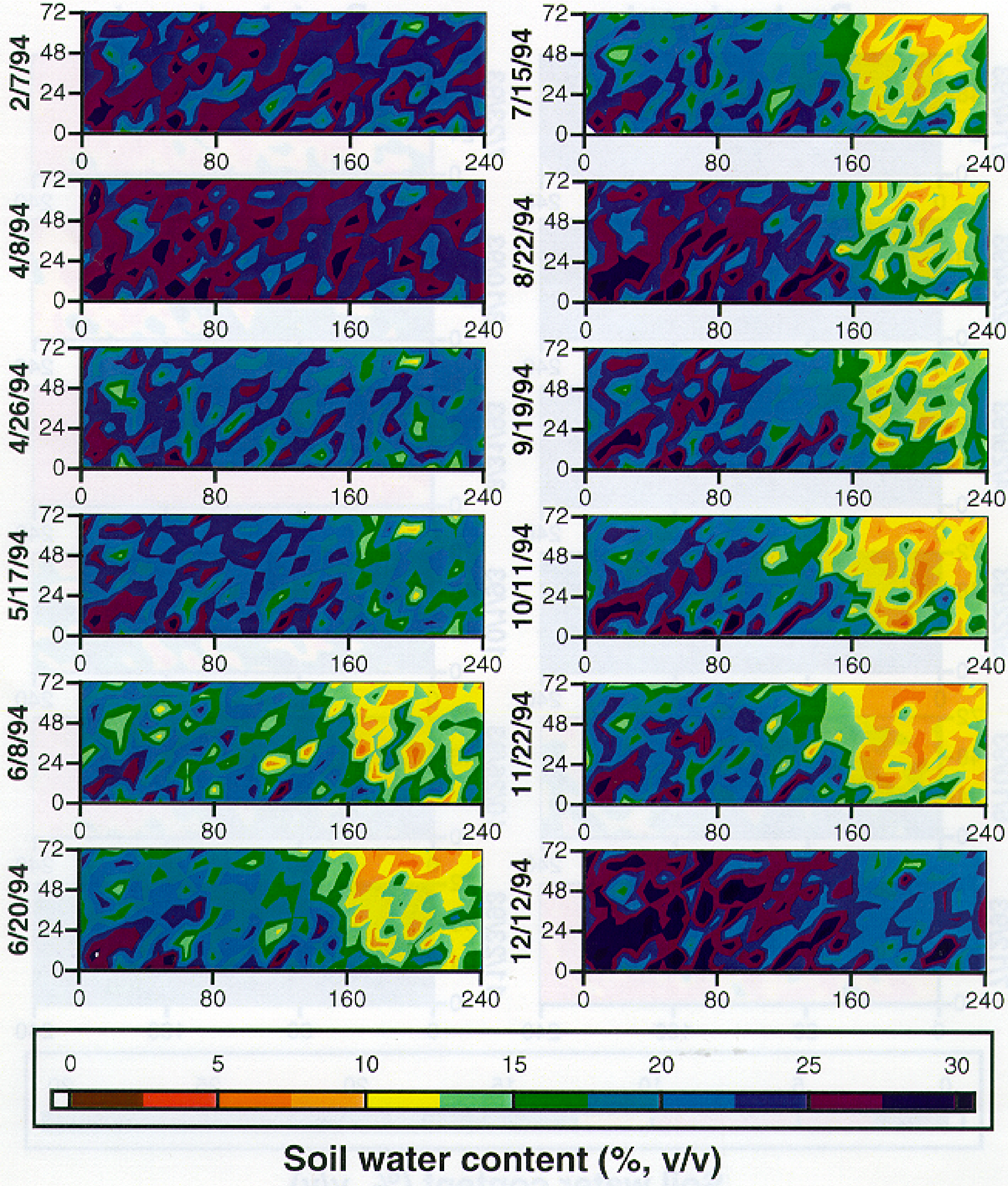


Fig. 9. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1994. March 4 and August 8 data were left off of this plot. Numbers along the x- and y-axis of each plot are meters.

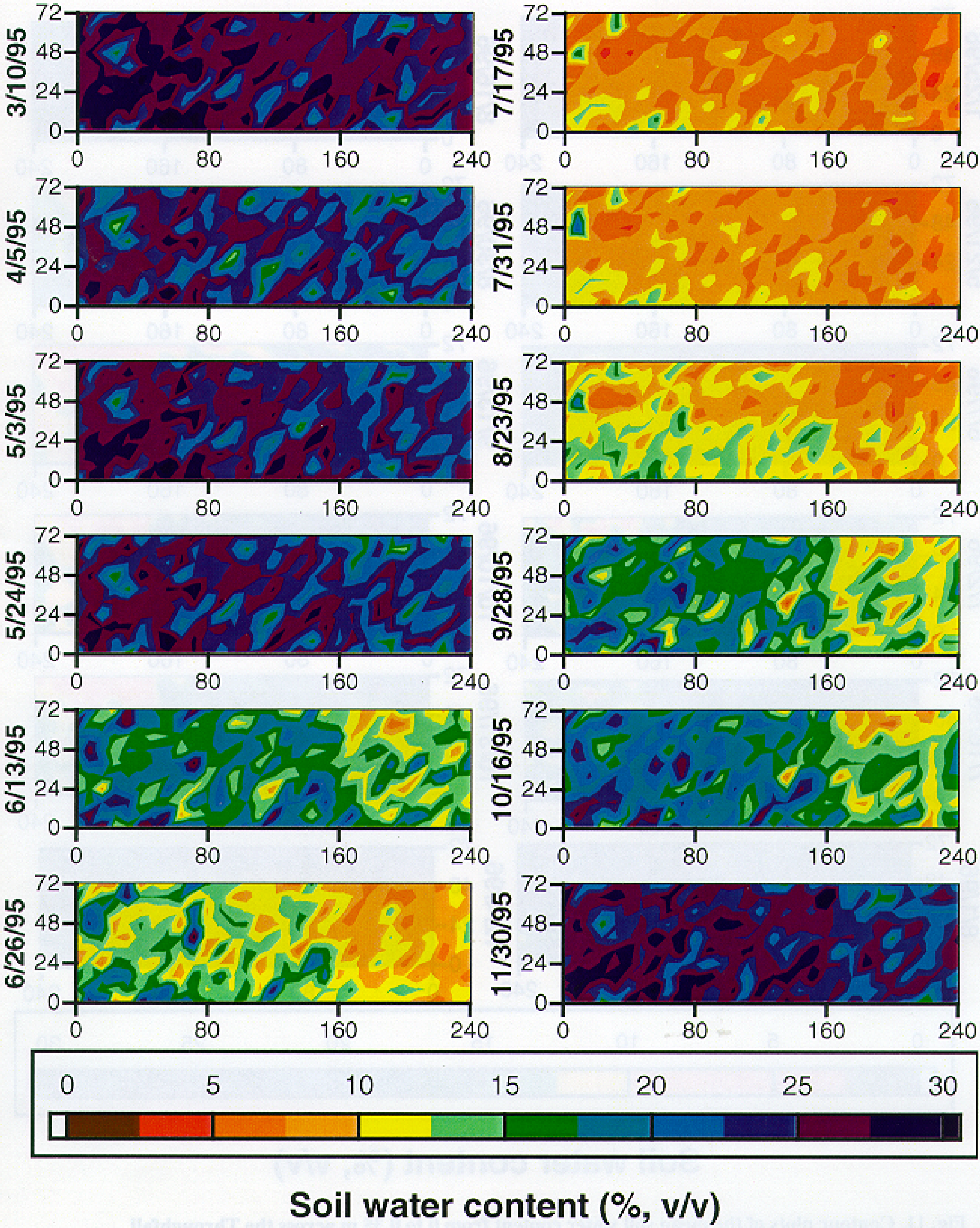


Fig. 10. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1995. The January 17 data were left off of the figure. Numbers along the x- and y-axis of each plot are meters.

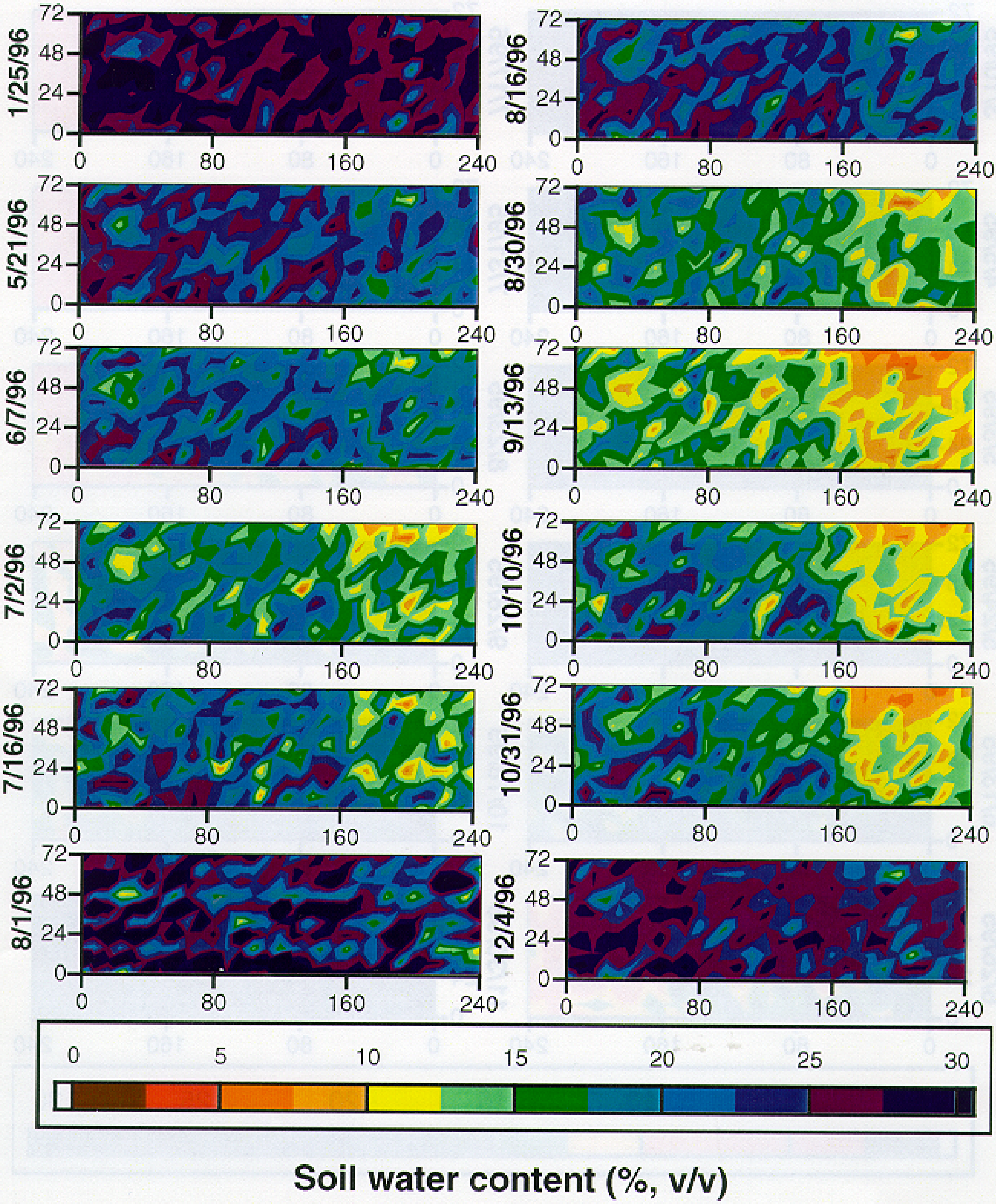


Fig. 11. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1996. February 29, March 27, and April 29 data were left off of this plot. Numbers along the x- and y-axis of each plot are meters.

3.3 TDE IMPACTS ON SOIL WATER POTENTIAL

For analysis of plant and/or soil responses to the TDE treatments we need to convert the soil water content data (Figs. 8–11; Tables A1–A9) to soil water potential as described previously. These estimates were broken out by treatment and slope position, yielding an upper-, middle-, and lower-slope position within each treatment. The upper-slope position includes transects 7 through 10; the middle, transects 4 through 6; and the lower, transects 1 through 3. The results of this process can be seen in Fig. 12 for the overall treatment means and depth increments. Individual treatment × slope soil water potentials are plotted for 1993–1996 in Fig. 13. Figures 12 and 13 emphasize the year-to-year differences in soil water status.

Even though soil water contents begin to decline with leaf-out in April and May, declining soil water potentials are not apparent for any year or treatment until after the beginning of June (i.e., after day 150). Another important distinction between the soil water content and soil water potential (Figs. 6 and 11) is the impression of the treatment effects on water in the 0.35- to 0.70-m soil depth. Soil water content data in Fig. 6 and statistical analyses in Appendix A suggest significant differences in soil water content for these deep soils. However, when these data are converted and expressed in terms of soil water potentials (Figs. 11 and 12) these treatment differences are no longer prevalent. The lack of differences in soil water potential below 0.35 m is important; we deduce from it that biological changes observed in response to the TDE treatments are driven by changes in surface soil water status.

Although ambient throughfall inputs in the dry 1995 growing season were comparable to the reduced dry-plot precipitation inputs in 1994 (Table 1), the resultant ambient soil water potentials were quite different. Soil water potentials were -0.2 MPa or greater in 1994 and most of 1996, but they often fell below -0.8 MPa and reached minimums >-1.0 MPa in 1995 (Figs. 12 and 13). Furthermore, although drought periods of 1993 and 1995 reached similar minimum soil water potentials (albeit at different times of the year), the duration of each year spent at severe stress levels was different. To quantify this year-to-year difference, a revised version of the PROSPER model (Goldstein et al. 1974, Huff et al. 1977, Vose and Swank 1994) coded using "Ithink" modeling software (High Performance Systems, Hanover, New Hamshire) for Macintosh computer systems was used to integrate the ambient soil water budgets for each year of the study. Daily outputs from this calculation representing the upper ambient position of the TDE area are superimposed over the observed data in Fig. 13. Summing these daily values for each year yields a cumulative index of drought stress (MPa days) that is useful for interyear comparisons. The wet 1994 and 1996 growing seasons had cumulative water potential exposures of -25 and -32 MPa days, which is much less than the values of -71 and -116 MPa days for 1993 and 1995. This index of water stress exposure duration clearly shows that 1995 was the most severe of the two drought years.

3.4 ADEQUACY OF THE 80- BY 80-m PLOT SIZE

The initial plot sizes were chosen based on the available space on the southeast slope making up the TDE area. However, we were concerned that the central trees of each plot be adequately away from the plot edges so that appropriate treatment conclusions could be drawn. Positioning the plots at the top of a ridge divide eliminated the concern over upslope incursion of water into the three TDE plots, and original plans left a 16-m buffer between treatment plots (8 m on the ends) in which no biological observations were made.

Figures 8–11 clearly show a sharp boundary between the ambient and dry plots of the TDE with little evidence of edge effects suggesting that our 16-m buffer is adequate. Conversely, we did have initial problems with even distribution of water onto the wet plot in the fall of 1993. The contour plots for August 10, October 1, and October 26 of 1993 all show an excess amount of water draining into the wet plot up and down the slope near the 80-m horizontal position (i.e., just after entering the wet plot). This problem was corrected in late 1993 by re-leveling the distribution pipes.

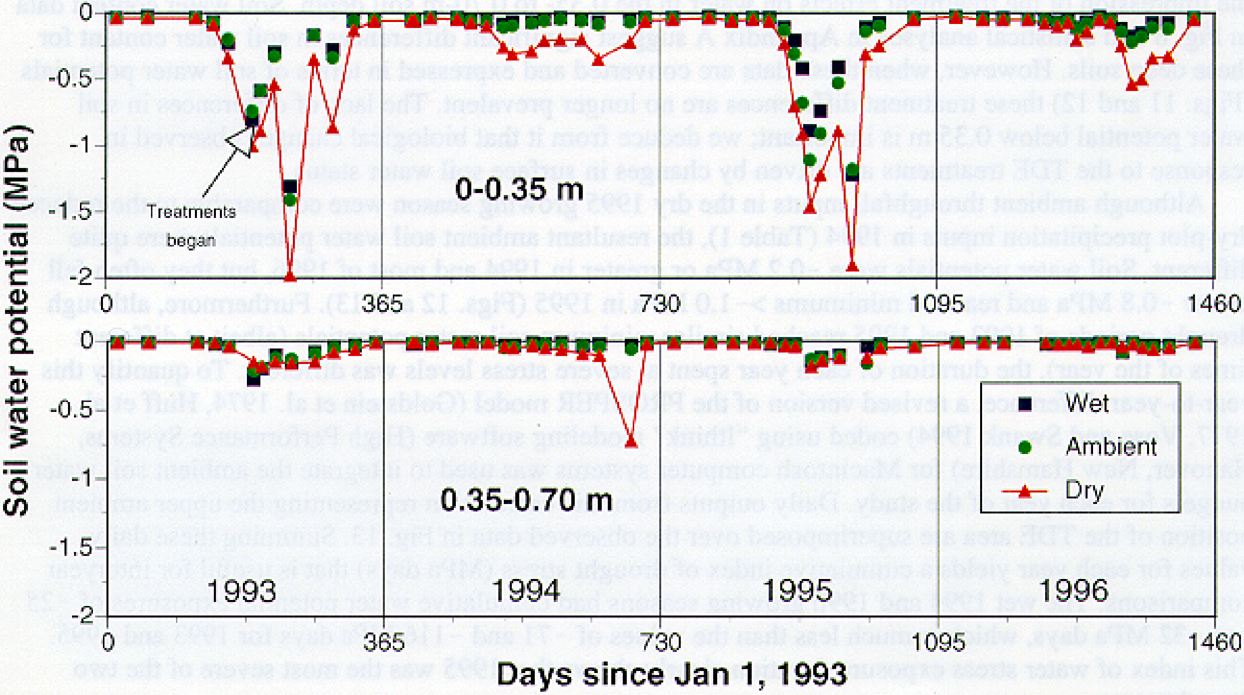


Fig. 12. Soil water potentials from 1993 through 1996 for the 0- to 0.35-m and the 0.35- to 0.7-m soil depths. Data are the mean values for the wet, ambient, and dry plots on the Walker Branch Throughfall Displacement Experiment. Throughfall displacement treatments were initiated on July 14, 1993 (see arrow at top left).

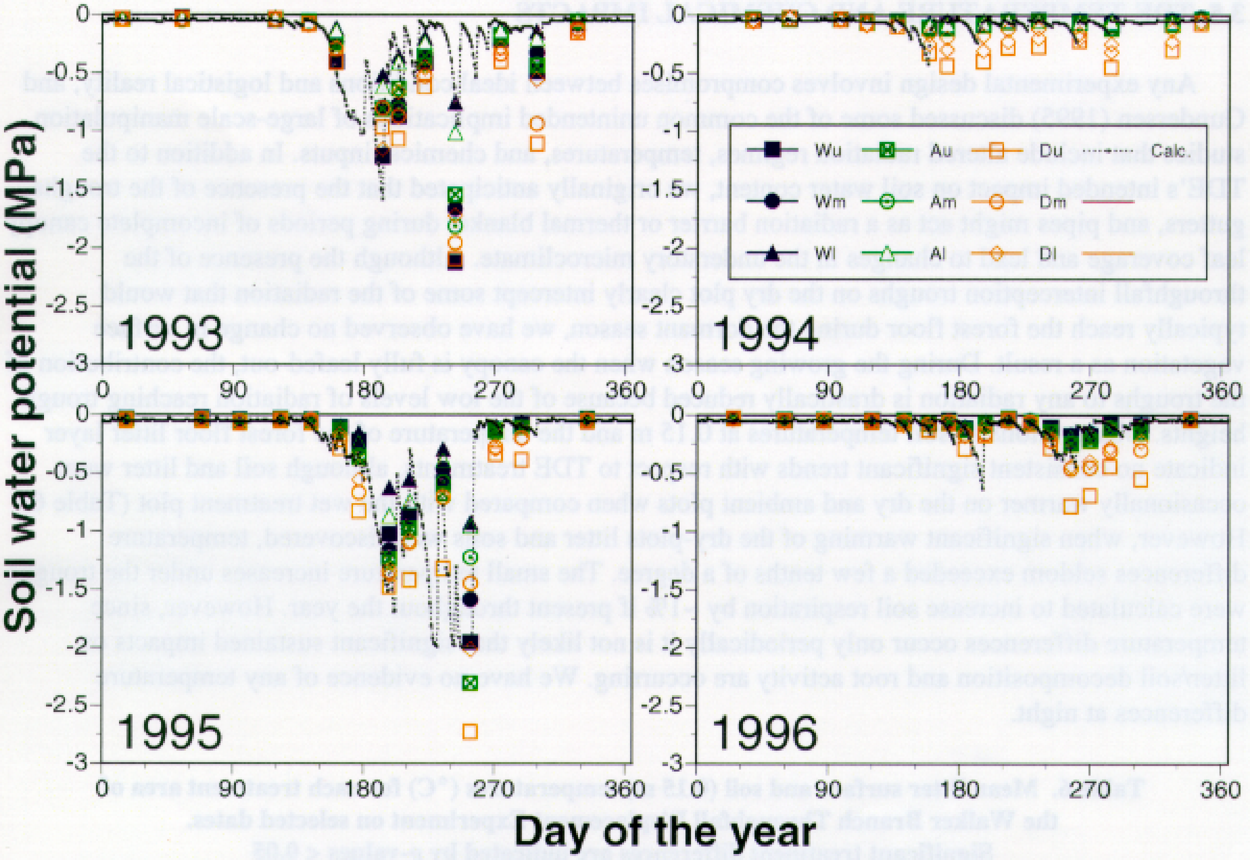


Fig. 13. Soil water potential for the 0- to 0.35-m depth for the nine treatment and slope positions of the Throughfall Displacement Experiment throughout 1993, 1994, 1995, and 1996. Soil water potentials were estimated from measured soil water contents and soil moisture release curves after correction for the coarse fraction of the soils. The wet, ambient, and dry plots are distinguished in the key (upper right) by uppercase W, A, and D, respectively; lower case l, m, and u represent the lower, middle, and upper slope positions. The dashed line represents the calculated daily water potential for the ambient upper slope position.

Windthrown- and lightning-damaged trees on the upper-west corner of the wet plot in June 1995 (Hanson et al. 1997) allowed us to further evaluate the effective horizontal rooting volume for large canopy *Quercus prinus* L. and *Quercus alba* L. trees. A comparison of the 0- to 0.35-m soil water contour plots for June 13, 1995, through September 28, 1995, show clear evidence of the impact of the loss of canopy on soil water in the dry plot. In particular, the July 17 and 31, 1995, plots show two wet zones in the upper-left corner of the wet plot, which correspond to the area in which the large tree canopies were removed. The maximum diameter for 'effective' rooting from any individual tree appeared to fall within a 16-m circle, with the damaged trunks near the center. Clearly, these trees may have had roots that were active beyond 8 m from the trunk of the tree, but the soil water patterns of Fig. 10 suggest that much of the influence of a given tree would fall within this distance from the trunk. Furthermore, because the trees were felled by wind one could argue that they had abnormally small root systems, and we might conservatively conclude that the effective rooting diameters suggested above are a minimum.

3.5 TDE TEMPERATURE AND CHEMICAL IMPACTS

Any experimental design involves compromises between ideal conditions and logistical reality, and Gundersen (1995) discussed some of the common unintended implications of large-scale manipulation studies that include altered radiation regimes, temperatures, and chemical inputs. In addition to the TDE's intended impact on soil water content, we originally anticipated that the presence of the troughs, gutters, and pipes might act as a radiation barrier or thermal blanket during periods of incomplete canopy leaf coverage and lead to changes in the understory microclimate. Although the presence of the throughfall interception troughs on the dry plot clearly intercept some of the radiation that would typically reach the forest floor during the dormant season, we have observed no change in surface vegetation as a result. During the growing season when the canopy is fully leafed-out, the contribution of the troughs to any radiation is drastically reduced because of the low levels of radiation reaching trough heights. Observations of soil temperatures at 0.15 m and the temperature of the forest floor litter layer indicate no consistent significant trends with respect to TDE treatments, although soil and litter were occasionally warmer on the dry and ambient plots when compared with the wet treatment plot (Table 6). However, when significant warming of the dry-plots litter and soils was discovered, temperature differences seldom exceeded a few tenths of a degree. The small temperature increases under the troughs were calculated to increase soil respiration by ~1% if present throughout the year. However, since temperature differences occur only periodically it is not likely that significant sustained impacts on litter/soil decomposition and root activity are occurring. We have no evidence of any temperature differences at night.

Table 6. Mean litter surface and soil (0.15 m) temperatures (°C) for each treatment area of the Walker Branch Throughfall Displacement Experiment on selected dates. Significant treatment differences are indicated by *p*-values < 0.05

ıble	Dormant season			Growing season			Treatment
94	2/1/95	4/17/94	4/25/94	6/29/95	7/1/94	10/1/96	
			Litter surface				
Wet	4.2	15.6	—	—	25.3	24.4	17.3
Ambient	5.9	16.4	—	—	24.9	23.4	19.6
Dry	5.9	15.8	—	—	26.3	23.3	19.8
p-value	<0.01	0.40	—	—	<0.01	<0.01	0.95
			0.15-m soil				
Wet	6.5	4.3	9.2	14.6	19.5	18.9	16.4
Ambient	6.5	4.1	9.2	14.6	19.5	18.8	16.4
Dry	6.6	4.9	9.5	14.7	19.6	18.8	16.7
p-value	0.15	<0.01	<0.01	0.12	0.06	0.67	<0.01

Chemicals from atmospheric deposition and canopy leaching are transferred with the throughfall precipitation from the dry treatment plots to the wet treatment plots, thus introducing another variable to the experiment in addition to the water manipulation. However, these chemical inputs appear to be small in comparison with the annual demand placed on the forest soils by the growing vegetation (Cole and Rapp 1981). The influence of the TDE on nutrient cycling processes in forest stands is discussed in Johnson et al. (1998).

3.6 COST OF IMPLEMENTING THE TDE

The TDE was constructed at an approximate initial cost of $300,000 (U.S. dollars). The dollar value is based on 1993 U.S. dollars. This initial capital outlay plus maintenance and quality assurance activities, which cost approximately $50,000 (U.S. dollars) per year from 1994 through 1996, yields a total cost of $450,000 (U.S. dollars) for three full years of operation. This three-year cost works out to be just under $37 U.S. dollars per square meter of ground measured, or $2030 (U.S. dollars) per mature dominant tree. We believe that this is a cost-effective method for large-scale forest manipulations.

4. CONCLUSIONS

The TDE design was developed to address questions related to sustained changes in forest ecosystem processes to a fractional change in precipitation inputs anticipated to coincide with global warming. Extreme scenarios, such as the 100% throughfall removal, were considered unsuitable for application in the eastern United States. Reductions in soil moisture anticipated from the TDE manipulation of -33% of the throughfall was anticipated to be comparable with the driest growing season of the 1980s drought (Cook et al. 1988), which was reported to have resulted in sapling mortality and reduced growth of some vegetation (Jones et al. 1993). Notwithstanding our avoidance of a 100% removal treatment, shorter-term (1- to 2-month) periods of 100% removal, simulating rare seasonal droughts, may be a justifiable scenario (Beier et al. 1995). The importance of seasonal drying sequences are discussed further in the companion to this paper (Hanson et al. 1997).

The TDE has operated continuously since treatments were initiated in July 1993 and throughout 1996. During this period, soil water measurements have shown that the TDE can produce significantly different hydrologic budgets for the wet, ambient, and dry plots in years having both high and low growing-season precipitation. Additionally, because of the substantial inter-annual variability in growing-season rainfall inputs we have obtained a much broader range of treatments than originally anticipated. The 1993 and 1995 growing seasons were exceptionally dry compared with the wet seasons in 1994 and 1996 (Fig. 13). This combined variability in annual and growing-season rainfall (Table 1) has allowed us to test not only the impact of a constant ±33% alteration of throughfall resulting from all incoming rainfall events, but to determine the influence of sustained severe droughts as well. Furthermore, the experimental design is able to produce these differences without significant confounding impacts on the understory microclimate.

5. REFERENCES

Beier, C., P. Gundersen, K. Hansen, and L. Rasmussen. 1995. Experimental manipulations of water and nutrient input to a Norway spruce plantation at Klosterhede, Denmark II. Effects on tree growth and nutrition. Plant Soil 168–69:613–22.

Bormann, F. H., and G. E. Likens. 1979. Pattern and Process in a Forested Ecosystem: Disturbance, Development, and the Steady State Based on the Hubbard Brook Ecosystem Study. Springer-Verlag, New York.

Cole, D. W., and M. Rapp. 1981. Elemental cycling in forest ecosystems. pp. 341–409. In D. E. Reichle (ed.), Dynamic Principles of Forest Ecosystems. Cambridge University Press, London.

Cook, E. R., M. A. Kablack, and G. C. Jacoby. 1988. The 1986 drought in the southeastern United States: How rare an event was it? J. Geophys. Res. 93(D11):14257–60.

Cooter, E .J., B. K. Eder, S. K. LeDuc, and L. Truppi. 1993. General circulation model output for forest climate change research and applications. Gen. Tech. Rep. SE-85. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. Asheville, N.C.

Cregg, B. M., J. E. Halpin, P. M. Dougherty, and R. O. Teskey. 1989. Comparative physiology and morphology of seedling and mature forest trees. pp. 111–18. In R. D. Noble, J. L. Martin, and K. F. Jensen (eds.), Air Pollution Effects on Vegetation Including Forest Ecosystems. United States Department of Agriculture, Washington, D.C.

Davis, M. B. 1989. Lags in vegetation response to greenhouse warming. Clim. Change 15:75–82.

Dougherty, P. M., and T. M. Hinckley. 1981. The influence of a severe drought on net photosynthesis of white oak (*Quercus alba*). Can. J. Bot. 59:335–341.

Drungil, C. E. C., T. J. Gish, and K. Abt. 1987. Soil moisture determination in gravelly soils with time domain reflectometry. Paper No. 87–2568. American Society of Agricultural Engineers, St. Joseph, Mich.

Eberhardt, L. L., and J. M. Thomas. 1991. Designing environmental field studies. Ecol. Monogr. 61:53–73.

Ellsworth, D. S., and P. B. Reich. 1992. Water relations and gas exchange of *Acer saccharum* seedlings in contrasting natural light and water regimes. Tree Physiol. 10:1–20.

Epron, D., E. Dreyer, and N. Breda. 1992. Photosynthesis of oak trees [*Quercus petraea* (Matt.) Liebl.] during drought under field conditions: diurnal course of net CO_2 assimilation and photochemical efficiency of photosystem II. Plant Cell Environ. 15:809–820.

Ginter-Whitehouse, D. L., T. M. Hinckley, and S. G. Pallardy. 1983. Spatial and temporal aspects of water relations of three tree species with different vascular anatomy. For. Sci. 29:317–329.

Goldstein, R. A., J. B. Mankin, and R. J. Luxmoore. 1974. Documentation of PROSPER—A model of atmosphere-soil-plant water flow. EDFB-IBP 73-9, UC–48. Oak Ridge National Laboratory.

Graham, R. L., M. G. Turner, and V. H. Dale. 1990. How increasing CO_2 and climate change affect forests. BioScience 40:575–87.

Gundersen, P. 1995. Unintended differences between natural and manipulated forest plots. pp. 335–43. In A. Jenkins, R. C. Ferrier, and C. Kirby (eds.), Ecosystem Manipulation Experiments: Scientific Approaches, Experimental Design and Relevant Results, Ecosystem Research Report No. 20, Commission of the European Communities, Luxembourg.

Hanson, P. J., D. E. Todd, N. T. Edwards, and M. A. Huston. 1995. Field performance of the Walker Branch Throughfall Displacement Experiment. pp. 307–13. In A. Jenkins, R. C. Ferrier, and C. Kirby, (eds.), Ecosystem Manipulation Experiments: Scientific Approaches, Experimental Design and Relevant Results, Ecosystem Research Report No. 20, Commission of the European Communities, Luxembourg.

Hinckley, T. M., J. P. Lassoie, and S. W. Running. 1978. Temporal and spatial variations in the water status of forest trees. For. Sci. Monogr. 20:1–72.

Houghton, J. T., L. G. Meira-Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.). 1996. Climate Change 1995: The Science of Climate Change. Cambridge University Press, New York.

Huff, D. D., R. J. Luxmoore, J. B. Mankin, and C. L. Begovich. 1977. TEHM: a terrestrial ecosystem hydrology model. EDFB/IBP-76/8, ORNL/NSF/EATC-27. Oak Ridge National Laboratory.

Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187–211.

Johnson, D. W., and R. I. VanHook (eds.). 1989. Analysis of Biogeochemical Cycling Processes in Walker Branch Watershed. Springer-Verlag, New York.

Johnson, D. W., P. J. Hanson, D. E. Todd, Jr., R. B. Susfalk, and C. F. Trettin. 1998. Precipitation change and soil leaching: field results and simulations from Walker Branch Watershed, Tennessee. Water Air Soil Pollut. (in press).

Jones, E. A., D. D. Reed, G. D. Mroz, H. O. Liechty, and P. J. Cattelino. 1993. Climate stress as a precursor to forest decline: paper birch in northern Michigan, 1985–1990. Can. J. For. Res. 23:229–33.

Kattenberg, A., F. Giorgi, H. Grassl, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer, T. Tokioka, A. J. Weaver, and T. M. L.Wigley. 1996. Climate models—projections of future climate. pp. 283–357. In J. T. Houghton et al. (eds.), Climate Change 1995: The Science of Climate Change. Cambridge University Press, New York.

Kirschbaum, M. U. F., and A. Fischlin. 1996. Climate change impacts on forests. pp. 95–129. In R. T. Watson, M. C. Zinyowera, and R. H. Moss (eds.), Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis. Cambridge University Press, New York.

Kliener, K. W., M. D. Abrams, and J. C. Schultz. 1992. The impact of water and nutrient deficiencies on the growth, gas exchange and water relations of red oak and chestnut oak. Tree Physiol. 11:271–87.

Kolb, T. E., K. C. Steiner, L. H. McCormick, and T. W. Bowersox. 1990. Growth response of northern red-oak and yellow-poplar seedlings to light, soil moisture and nutrients in relation to ecological strategy. For. Ecol. Manage. 38:65–78.

Melillo, J. M., T. V. Callaghan, F. I. Woodward, E. Salati, and S. K. Sinha. 1990. Effects on ecosystems. pp. 282–310. In J. T. Houghton, G. J. Jenkins, and J. J. Ephraums (eds.), Climate Change—The IPCC Scientific Assessment. Cambridge University Press, New York.

Mellilo, J. M., I. C. Prentice, G. D. Farquhar, E.-D. Schulze, and O.E. Sala. 1996. Terrestrial biotic responses to environmental change and feedbacks to climate. pp. 445–81. In J. T. Houghton et al. (eds.), Climate Change 1995: The Science of Climate Change. Cambridge University Press, New York.

Mohnen, V. A., and W.-C. Wang. 1992. An overview of global warming. Environ. Toxicol. Chem. 11:1051–59.

Mooney, H. 1991. Biological response to climate change: an agenda for research. Ecol. Appl. 1:112–17.

Mooney, H. A., B. G. Drake, R. J. Luxmoore, W. C. Oechel, and L. F. Pitelka. 1991. Predicting ecosystem responses to elevated CO_2 concentrations. BioScience 41:96–104.

Mulholland, P. J. 1993. Hydrometric and stream chemistry evidence of three storm flowpaths in Walker Branch Watershed. J. Hydrol. 151:291–316.

Neilson, R. P., G. A. King, R. L. DeVelice, J. Lenihan, D. Marks, J. Dolph, B. Campbell, and G. Glick. 1989. Sensitivity of ecological landscapes and regions to global climatic change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oreg.

Overpeck, J. T., P. J. Bartlein, and T. Webb. 1991. Potential magnitude of future vegetation change in eastern North America: comparisons with the past. Science 254:692–95.

Pastor, J., and W. M. Post. 1988. Response of northern forests to CO_2-induced climate change. Nature 334:55–58.

Peters, L. N., D. F. Grigal, J. W. Curlin, and W. J. Selvidge. 1970. Walker Branch Watershed Project: chemical, physical and morphological properties of the soils of Walker Branch Watershed. ORNL-TM-2968. Oak Ridge National Laboratory.

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

Ragsdale, H. L., S. E. Lindberg, G. M. Lovett, and D. A. Schaefer. 1992. Atmospheric deposition and throughfall fluxes of base cations. pp. 235–53. In D. W. Johnson and S. E. Lindberg (eds.), Atmospheric Deposition and Nutrient Cycling. Springer-Verlag, New York.

Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy. 1990. Potential evapotranspiration and the likelihood of future drought. J. Geophys. Res. 95(D7):9983–10004.

Rind, D., C. Rosenzweig, and R. Goldberg. 1992. Modelling the hydrologic cycle in assessments of climate change. Nature 358:119–22.

Schneider, S. H. 1989. The greenhouse effect: science and policy. Science 243:771–81.

Smith, J. B., and D. A. Tirpak (eds.). 1989. The potential effects of global climate change on the United States. U.S. Environmental Protection Agency, Hemisphere Publishing Corp., Washington, D.C.

Swank, W. T., and D. A. Crossley Jr., (eds.). 1988. Forest Hydrology and Ecology at Coweeta. Springer-Verlag, New York.

Solomon, A. M. 1986. Transient response of forests to CO_2-induced climate change: Simulation modeling experiments in eastern North America. Oecologia 68:567–79.

Topp, G. C., and J. L. Davis. 1985. Measurement of soil water content using time domain reflectometry (TDR): a field evaluation. Soil Sci. Soc. Am. J. 49:19–24.

Turner, S. J., R. V. O'Neill, W. Conley, M. R. Conley, and H. C. Humphries. 1991. Pattern and scale: Statistics for landscape ecology. pp. 17–49. In Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity. Springer-Verlag, New York.

Turner, R. S., P. J. Hanson, M. A. Huston, C. T. Garten Jr., and P. J. Mulholland. 1993. A large-scale throughfall manipulation experiment on Walker Branch Watershed, pp. 96–105. In L. Rasmussen, T. Brydges, and P. Mathy (eds.), Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems, Ecosystem Research Report No. 4. Commission of the European Communities, Luxembourg.

Vose, J. M., and W. T. Swank. 1994. Effects of long-term drought on the hydrology and growth of a white pine plantation in the southern Appalachians. For. Ecol. Manage. 64:25–39.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones. 1984. Predicting plant productivity and water resources. Nature 312:102–103.

Woodward, F. I. 1992. Tansley Review No. 41: Predicting plant responses to global environmental change. New Phytol. 122:239–51.

APPENDIX

Table A1. 1992 pretreatment percent soil water content in the 0- to 0.35-m, or the 0- to 0.7-m depth layer, categorized by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-value for pretreatment main effects of proposed treatment location, slope position, and their interaction are provided.

Pretreatment/slope	Day of the year (0- to 0.35-m depth)						Day of the year (0- to 0.7-m depth)					
	192	225	253	283	323	349	192	225	253	283	323	349
							Measured values					
Wet positions												
Lower	24.2	20.9	16.2	19.6	24.8	26.9	23.0	19.8	16.9	18.7	23.4	25.1
Middle	22.6	15.8	10.3	14.1	22.2	24.8	22.4	16.6	13.1	14.2	23.4	23.9
Upper	21.6	14.4	9.5	14.5	20.8	24.7	21.2	16.1	11.9	14.9	20.6	24.1
Ambient												
Lower	24.4	19.8	15.3	20.4	24.0	26.7	24.4	19.9	17.4	20.4	23.6	26.7
Middle	20.5	17.8	12.0	17.3	22.5	25.4	23.0	19.5	15.4	17.9	25.1	25.4
Upper	22.0	16.0	10.8	15.3	22.5	25.0	21.1	17.3	12.6	16.3	23.6	25.0
Dry positions												
Lower	20.7	15.0	11.0	15.0	20.8	24.2	23.2	19.2	15.3	17.0	24.8	24.2
Middle	21.0	15.4	9.9	15.5	22.3	25.8	24.0	17.1	13.1	16.6	26.0	25.8
Upper	19.6	12.7	8.7	13.4	21.5	24.1	21.2	15.2	11.1	15.3	21.1	24.1
							Statistical values					
Precent of rods measured	45	97	97	99	70	97	47	98	95	99	67	97
Covariate ANOVA *p*-values												
Pretreatment location	0.01	0.0	0.0	0.0	0.03	0.06	0.66	0.03	0.00	0.00	0.19	0.15
Slope	0.01	0.0	0.0	0.0	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.27
Treatment × slope	0.41	0.0	0.0	0.0	0.0	0.01	0.73	0.47	0.54	0.01	0.60	0.70

Table A2. 1993 percent soil water content in the 0- to 0.35-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the p-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year											
	(Pretreatment dates)						(During treatment dates)					
	14	55	119	142	161	193	204	222	243	274	299	327
							Measured values					
Wet												
Lower	26.5	27.1	26.5	23.1	18.0	10.8	12.5	15.2	9.5	18.2	17.0	24.2
Middle	25.9	26.7	26.0	20.9	14.1	9.2	9.3	12.5	7.0	15.2	12.7	22.6
Upper	24.4	25.6	23.7	20.7	11.6	7.7	8.7	11.4	6.2	14.2	10.8	20.3
Ambient												
Lower	26.2	26.7	26.7	22.6	17.0	10.1	11.7	14.1	8.4	17.0	14.8	23.7
Middle	24.6	24.5	24.4	20.1	14.3	9.1	9.1	11.4	6.7	14.6	11.5	21.5
Upper	25.4	25.4	24.9	21.7	13.5	8.9	9.6	11.8	6.9	15.0	11.0	21.7
Dry												
Lower	24.2	24.9	24.0	19.4	13.0	7.8	9.6	11.0	6.7	13.0	10.2	18.8
Middle	25.5	25.6	25.7	19.8	12.9	9.0	8.7	10.5	6.4	12.3	8.5	17.4
Upper	24.7	25.1	24.0	19.4	11.3	8.2	7.9	9.7	6.1	11.4	7.8	16.0
							Statistical values					
Percent of rods measured	99	72	93	99	95	96	96	99	99	99.6	99.3	99.3
Covariate ANOVA p-values												
Treatment	0.76	0.33	0.91	0.15	0.28	0.37	0.04	0.00	0.00	0.00	0.00	0.00
Slope	0.40	0.03	0.06	0.00	0.86	0.01	0.00	0.18	0.01	0.12	0.00	0.00
Treatment × slope	0.98	0.44	0.92	0.06	0.59	0.05	0.02	0.13	0.04	0.09	0.07	0.04
Covariate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A3. 1993 percent soil water content in the 0- to 0.7-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year											
	(Pretreatment dates)						(During treatment dates)					
	14	55	119	142	161	193	204	222	243	274	299	327
	Measured values											
Wet												
Lower	26.3	25.9	25.3	22.6	17.7	10.8	11.7	14.2	11.0	16.8	17.8	22.2
Middle	27.1	26.6	24.3	22.1	15.8	9.8	10.8	14.2	9.9	15.2	15.7	21.7
Upper	25.6	25.1	24.9	20.7	14.6	8.6	9.6	12.3	8.8	14.1	13.3	19.3
Ambient												
Lower	26.2	26.5	26.1	23.1	18.0	11.5	12.1	14.3	11.0	16.1	16.5	21.9
Middle	24.6	25.7	25.4	21.8	16.4	9.9	10.8	12.3	10.1	15.0	14.5	20.7
Upper	25.4	24.7	26.0	21.8	15.6	9.5	9.6	12.0	9.2	14.2	13.1	20.1
Dry												
Lower	24.2	26.5	26.2	22.0	16.7	10.6	11.4	12.3	10.5	14.3	14.3	19.7
Middle	25.5	27.0	26.5	21.9	15.8	10.0	10.1	11.6	9.2	12.3	11.4	16.8
Upper	24.7	25.5	25.6	21.9	14.1	8.8	9.0	10.5	8.4	10.9	9.9	14.9
	Statistical values											
Percent of rods measured	92	78	96	91	97	96	94	93	94	96	94	96
Covariate ANOVA *p*-values												
Treatment	0.06	0.39	0.14	0.04	0.21	0.08	0.06	0.00	0.21	0.00	0.00	0.00
Slope	0.00	0.00	0.06	0.01	0.03	0.18	0.11	0.09	0.15	0.95	0.40	0.00
Treatment × slope	0.01	0.15	0.18	0.71	0.97	0.38	0.06	0.01	0.09	0.82	0.21	0.04
Covariate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A4. 1994 percent soil water content in the 0- to 0.35-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year													
	38	62	98	116	137	159	171	196	213	234	262	284	326	346
Measured values														
Wet														
Lower	24.6	25.8	25.4	22.3	23.4	21.2	22.9	23.2	23.1	25.9	23.9	24.0	22.9	26.2
Middle	24.5	25.8	25.3	22.4	22.3	19.1	20.7	21.4	23.3	24.6	23.1	22.1	21.5	26.8
Upper	23.3	24.2	24.7	21.6	22.2	18.2	19.0	19.9	22.5	23.9	22.3	19.3	19.3	25.5
Ambient														
Lower	24.4	25.3	25.3	21.5	22.4	19.9	20.5	21.9	23.7	24.5	22.9	22.3	21.1	24.9
Middle	23.1	24.1	24.6	21.6	21.1	17.5	18.6	20.0	22.7	23.6	21.4	19.4	18.6	24.8
Upper	24.2	24.9	25.1	21.7	22.1	17.5	17.4	19.1	21.6	22.4	20.8	17.3	17.0	25.2
Dry														
Lower	21.9	23.4	23.2	19.1	18.7	15.6	14.7	15.3	17.1	17.5	16.0	13.6	12.5	22.3
Middle	23.5	24.8	24.4	20.4	18.6	13.6	12.8	12.7	14.1	14.8	14.7	12.5	10.7	22.6
Upper	22.5	23.5	24.0	20.2	18.3	12.2	11.1	11.4	12.8	13.1	13.9	10.9	9.8	20.9
Statistical values														
Percent of rods measured	99	100	99.3	98	99.6	98	99.3	99	99	96	99.3	98	99.3	99.7
Covariate ANOVA *p*-values														
Treatment	0.09	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slope	0.00	0.11	0.32	0.00	0.06	0.00	0.00	0.00	0.58	0.00	0.01	0.00	0.00	0.09
Treatment × slope	0.57	0.35	0.99	0.14	0.23	0.15	0.12	0.12	0.00	0.95	0.00	0.59	0.10	0.00
Covariate	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table A5. 1994 percent soil water content in the 0- to 0.7-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year													
	38	62	98	116	137	159	171	196	213	234	262	284	326	346
							Measured values							
Wet														
Lower	23.6	26.0	26.2	23.1	23.1	20.4	21.8	23.1	22.9	24.5	22.4	21.8	24.1	24.6
Middle	24.5	26.7	27.6	23.8	23.8	19.2	21.0	22.7	23.2	25.1	21.7	21.4	23.5	26.3
Upper	23.2	25.8	26.5	22.8	22.8	18.4	19.5	22.1	22.0	23.4	20.3	20.5	22.4	25.0
Ambient														
Lower	24.5	25.7	25.9	23.4	23.4	19.4	20.0	22.7	23.2	24.5	21.7	21.1	23.0	25.2
Middle	24.1	25.4	26.0	22.5	22.5	17.4	18.7	21.6	22.3	23.4	21.4	19.0	21.2	24.9
Upper	24.0	25.8	25.7	23.1	23.1	16.8	17.4	20.3	20.9	21.6	19.2	16.5	19.4	24.2
Dry														
Lower	24.4	26.2	26.6	23.3	23.3	17.6	16.9	19.2	19.1	19.1	17.4	15.2	17.2	23.5
Middle	24.4	26.4	27.0	23.6	23.6	15.7	14.9	15.8	15.8	15.3	14.5	13.0	14.1	21.9
Upper	23.5	25.6	26.3	23.0	23.0	14.0	12.9	14.5	13.5	13.6	12.5	11.1	12.5	20.7
							Statistical values							
Percent of rods measured	98	100	96	100	100	99	99.3	97	99	98	99	98	100	100
Covariate ANOVA *p*-values														
Treatment	0.06	0.01	0.00	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slope	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.04
Treatment × slope	0.08	0.59	0.53	0.43	0.43	0.22	0.06	0.00	0.00	0.00	0.10	0.00	0.00	0.00
Covariate	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table A6. 1995 percent soil water content in the 0- to 0.35-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year														
	17	69	96	123	144	164	177	188	198	212	235	254	271	289	334
								Measured values							
Wet															
Lower	26.3	26.8	24.4	26.3	24.8	19.6	16.4	—	10.2	10.6	13.2	8.8	19.1	21.4	25.7
Middle	25.8	26.6	24.0	25.4	24.3	17.3	13.7	—	8.0	8.8	11.2	7.1	17.7	19.8	25.5
Upper	25.4	26.7	23.3	25.0	23.6	18.2	14.1	11.5	8.2	8.7	10.1	6.4	17.2	19.1	25.1
Ambient															
Lower	25.3	26.0	23.5	25.3	24.0	18.3	14.2	—	8.9	9.4	11.9	8.6	17.2	19.1	25.6
Middle	24.7	25.6	23.0	24.1	23.8	16.6	12.4	—	7.8	8.4	10.4	7.8	16.1	18.5	25.2
Upper	24.7	25.6	22.5	24.1	23.7	16.8	11.7	9.6	7.5	8.2	9.4	5.9	16.6	17.8	24.4
Dry															
Lower	23.1	23.7	21.3	23.2	21.7	15.4	10.3	—	7.3	8.0	9.3	6.3	12.8	14.4	22.8
Middle	23.8	25.2	22.5	23.5	23.0	14.3	9.6	—	7.4	8.0	9.4	7.2	13.2	14.8	24.1
Upper	22.2	23.6	20.6	22.3	20.9	12.7	8.7	8.6	7.0	7.1	7.3	5.5	12.0	11.5	21.8
								Statistical values							
Percent of rods measured	99.7	99.7	99.7	100	99	97	99	40	99	99	99.7	48	99.3	96	99.7
Covariate ANOVA *p*-values															
Treatment	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00
Slope	0.00	0.00	0.00	0.00	0.00	0.69	0.77	—	0.35	0.84	0.00	0.00	0.00	0.00	0.18
Treatment × slope	0.01	0.01	0.09	0.03	0.03	0.00	0.29	—	0.68	0.80	0.77	0.34	0.14	0.00	0.54
Covariate	.00	.00	.00	.00	.00	.00	.00	0.00	.00	.00	.00	.00	.00	.00	.00

Table A7. 1995 percent soil water content in the 0- to 0.7-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year														
	17	69	96	123	144	164	177	188	198	212	235	254	271	289	334
								Measured values							
Wet															
Lower	25.6	27.3	23.8	26.4	22.8	20.0	17.8	—	10.8	11.3	12.9	—	17.7	21.8	21.1
Middle	27.5	28.2	23.9	26.8	23.0	19.3	17.6	—	10.6	11.3	13.1	—	17.9	21.6	23.7
Upper	26.4	27.4	24.4	26.1	23.3	20.0	17.5	—	10.0	10.8	12.4	—	18.1	20.6	19.8
Ambient															
Lower	26.7	27.4	24.4	26.8	22.9	19.4	17.4	—	11.5	11.8	12.9	—	14.2	20.3	21.8
Middle	26.4	26.8	23.3	26.5	23.7	19.4	16.7	—	10.2	10.7	11.9	—	15.4	19.5	22.4
Upper	25.5	26.6	23.7	25.0	22.3	16.4	14.8	—	9.4	10.0	11.2	—	13.5	17.8	19.5
Dry															
Lower	26.2	26.9	23.7	26.0	23.1	18.6	15.2	—	10.4	11.2	12.0	—	14.4	17.9	21.1
Middle	25.9	27.4	22.5	25.5	23.3	17.0	14.3	—	9.5	10.1	10.8	—	13.7	15.2	22.0
Upper	24.9	26.3	23.8	24.8	22.4	15.4	12.6	—	8.5	9.3	10.3	—	11.2	13.4	18.7
								Statistical values							
Percent of rods measured	99.7	97	100	98	97	100	99	0	97	98	95	0	49	93	96
Covariate ANOVA *p*-values															
Treatment	0.00	0.00	0.07	0.00	0.47	0.00	0.00	—	0.00	0.00	0.00	—	0.00	0.00	0.38
Slope	0.00	0.00	0.00	0.00	0.00	0.13	0.12	—	0.31	0.66	0.58	—	0.59	0.03	0.00
Treatment × slope	0.01	0.32	0.09	0.06	0.36	0.00	0.10	—	0.20	0.11	0.05	—	0.22	0.01	0.79
Covariate	.00	.00	.00	.00	.00	.00	.00	—	.00	.00	.00	—	.00	.00	.00

Table A8. **1996 percent soil water content in the 0- to 0.35-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.**

Treatment/slope	Day of the year																
	25	60	87	120	142	159	173	184	198	214	229	243	257	270	284	305	339
	Measured values																
Wet																	
Lower	28.1	24.9	25.5	24.6	24.2	22.7	22.7	19.5	23.3	25.9	23.8	18.2	16.3	17.2	20.7	21.9	25.8
Middle	28.4	24.4	24.6	23.4	23.6	20.7	21.2	17.9	19.8	26.7	23.2	16.8	14.6	16.2	19.6	20.0	25.8
Upper	27.7	23.8	24.0	22.8	23.3	20.0	22.7	17.6	20.3	27.6	22.2	18.3	15.2	15.4	19.7	19.1	26.2
Ambient																	
Lower	27.8	24.5	24.1	24.7	23.1	21.5	21.6	18.6	21.6	27.1	24.1	17.2	15.5	16.4	19.1	20.0	24.9
Middle	27.7	23.7	24.0	21.9	22.9	21.2	22.7	17.5	19.1	25.1	23.1	16.9	14.2	15.3	18.2	17.6	25.1
Upper	27.9	24.0	24.3	22.8	23.1	19.9	21.8	17.0	20.4	25.8	22.2	16.5	13.5	14.1	17.1	16.0	25.6
Dry																	
Lower	25.4	22.0	22.4	23.4	19.5	19.1	19.3	15.2	18.4	23.7	21.4	14.0	11.2	11.5	13.1	14.2	22.8
Middle	27.3	24.1	24.3	23.3	21.7	19.8	21.6	15.7	16.1	23.9	21.9	14.3	11.0	11.1	12.7	12.8	25.1
Upper	26.4	22.4	22.5	21.7	20.0	16.8	20.7	12.8	15.3	24.4	19.4	12.8	8.9	9.3	11.0	10.2	23.6
	Statistical values																
Percent of rods measured	92	97	97	91	97	98	98	99	93	99	99.3	87	97	96	97	99	97
Covariate ANOVA *p*-values																	
Treatment	0.13	0.68	0.52	0.75	0.00	0.00	0.15	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Slope	0.27	0.48	0.36	0.00	0.14	0.00	0.03	0.00	0.00	0.38	0.00	0.39	0.00	0.00	0.05	0.00	0.00
Treatment × slope	0.88	0.68	0.38	0.27	0.53	0.18	0.01	0.33	0.40	0.62	0.41	0.07	0.13	0.73	0.70	0.00	0.06
Covariate	.00	.00	.00	.00	.00	.00	.00	0.00	.00	.00	.00	.00	0.00	.00	.00	.00	0.00

Table A9. 1996 percent soil water content in the 0- to 0.7-m depth layer by treatment and slope position. Percentage of all rod pairs measured successfully on each date is indicated, and the *p*-values for main effects of treatment site, slope position, and their interaction are provided.

Treatment/slope	Day of the year																
	25	60	87	120	142	159	173	184	198	214	229	243	257	270	284	305	339
	Measured values																
Wet																	
Lower	26.0	24.9	25.3	—	24.1	21.0	21.6	20.6	22.6	27.2	23.1	18.7	20.1	17.4	19.5	20.3	25.3
Middle	27.0	25.7	26.2	—	22.8	22.7	21.6	20.5	21.5	26.9	23.8	19.2	20.1	17.2	19.3	20.3	26.1
Upper	26.4	24.9	25.5	—	22.2	21.1	22.2	20.1	20.4	25.8	23.5	19.4	19.2	18.0	19.7	20.0	25.3
Ambient																	
Lower	26.4	25.5	25.6	—	24.3	21.8	22.3	20.3	21.4	27.7	24.0	19.5	21.1	17.8	19.5	19.5	25.8
Middle	26.1	25.2	25.1	—	22.4	22.1	21.9	20.2	20.7	25.8	23.7	19.3	20.8	16.6	18.0	18.5	25.2
Upper	26.4	24.7	25.1	—	22.3	21.2	23.0	19.5	18.4	24.8	22.8	17.9	16.2	14.8	16.2	16.3	24.6
Dry																	
Lower	26.2	25.3	25.6	—	23.5	21.2	21.2	19.0	19.4	26.2	23.6	18.6	19.1	15.9	16.3	16.4	25.6
Middle	26.3	25.3	25.9	—	21.7	21.6	21.4	18.4	17.2	25.4	22.7	17.5	16.0	13.8	14.4	14.6	25.7
Upper	26.0	24.0	24.9	—	21.2	19.4	21.0	16.9	16.3	25.3	21.5	15.4	14.0	12.4	12.3	12.4	24.6
	Statistical values																
Percent of rods measured	98	97	99	0	96	96	78	97	99	99.3	96	99	96	96	99	96	99
Covariate ANOVA *p*-values																	
Treatment	0.10	0.10	0.84	—	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Slope	0.00	0.13	0.68	—	0.00	0.00	0.22	0.14	0.00	0.00	0.07	0.02	0.00	0.48	0.18	0.00	0.07
Treatment × slope	0.10	0.49	0.27	—	0.94	0.14	0.36	0.35	0.74	0.33	0.05	0.00	0.01	0.00	0.00	0.00	0.07
Covariate	.00	.00	.00	—	.00	.00	.00	0.00	.00	.00	.00	.00	0.00	.00	.00	.00	0.00

APPENDIX B: PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SOILS OF THE WALKER BRANCH THROUGHFALL DISPLACEMENT EXPERIMENT SITE

Initial characteristics of the TDE typic Paleudult soils (Fullerton cherty silt loam). Most data are from Tables 55–58 of Peters et al. (1970), supplemented by measurements on the TDE site.

Physical characteristics (sil=silt, sic=silty clay, c=clay)

Horizon	Depth (cm)	Bulk density (g cm-3)	Texture	Sand (%)	Silt (%)	Clay (%)	Peters Coarse Fraction % (g/g)	Peters Coarse Fraction %(v/v)	Joslin/Wolfe Coarse Fraction %(v/v)
A	0-7	1.06	sil	34	63	3	30	12.0	14.2
E	7-33	1.27	sil	28	60	12	29	13.9	14.2
AB	33-43	1.43	sil	28	64	8	36	19.4	17
B1	43-51	1.31	sil	24	56	20	31	15.3	17
B21t	51-71	1.29	sic	17	43	40	18	8.8	17
B22t	71-107+	1.2	c	13	36	51	17	7.7	--

Exchangeable cations (CEC = cation exchange capacity)

Horizon	pH	CEC (meq/100g)	Ca (meq/100g)	Mg (meq/100g)	K (meq/100g)	Base saturation (%)
A	4.5	5.64	0.68	0.17	0.11	29
E	4.2	1.94	0.09	0.04	0.03	9
AB	4.4	2.08	0.12	0.04	0.04	14
B1	4.2	2.73	0.08	0.04	0.03	7
B21t	4.2	5.42	0.1	0.11	0.03	6
B22t	4.2	8.92	0.15	0.2	0.05	6

Elemental analysis (O.M. = organic matter)

Horizon	Ca (%)	Mg (%)	K (%)	Fe (%)	N (%)	P (%)	O.M. (%)
A	0.06	0.08	0.37	0.96	0.158	0.02	6.54
E	0.05	0.1	0.45	1.47	0.05	0.02	1.75
AB	0.03	0.1	0.4	1.43	0.031	0.01	0.65
B1	0.06	0.12	0.56	1.68	0.031	0.02	0.62
B21t	0.04	0.22	0.57	2.19	0.041	0.01	0.63
B22t	0.05	0.23	0.72	2.48	0.039	0.02	0.62

Root distribution by depth (J. D. Joslin, Tennessee Valley Authority, personal communication)

Depth (cm)	% of all roots
0-30	66
30-60	23

```
60-90         11
```

REFERENCE

Peters, L. N., D. F. Grigal, J. W. Curlin, and W. J. Selvidge. 1970. *Walker Branch Watershed Project: Chemical, physical and morphological properties of the soils of Walker Branch Watershed*. ORNL/TM-2968. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

APPENDIX C: SPECIES NAMES AND SPECIES CODES (VARIABLE SPC IN THE DATA FILES) OF THE WALKER BRANCH THROUGHFALL DISPLACEMENT EXPERIMENT SITE

AR = *Acer rubrum*
AS = *Acer saccharum*
Aralia = *Aralia spinosa*
Carpins = *Carpinus caroliniana*
Carya = *Carya* sp.
Cercis = *Cercis canadensis*
CF = *Cornus florida*
FG = *Fagus grandifolia*
Fraxinus = *Fraxinus* sp.
JV = *Juniperus virginiana*
NS = *Nyssa sylvatica*
LS = *Liquidambar styraciflua*
LT = *Liriodendron tulipifera*
Mag = *Magnolia tripetala*
OA = *Oxydendrum arboreum*
PE = *Pinus echinata*
PS = *Pinus strobus*
PV = *Pinus virginiana*
Prunus = *Prunus serotina*
QA = *Quercus alba*
QP = *Quercus prinus*
QR = *Quercus rubra*
QS = *Quercus stellata*
QV = *Quercus velutina*
Rhamnus = *Rhamnus* sp.
Sass = *Sassafras albidum*

APPENDIX D: LISTING OF THROUGHFALL DISPLACEMENT EXPERIMENT PUBLICATIONS

A. INTRODUCTORY PAPERS AND SUMMARIES

Hanson, P. J., D. E. Todd, D. W. Johnson, J. D. Joslin, and E. G. O'Neill (in press). Responses of eastern deciduous forests to precipitation change. In J. F. Weltzin and G. R. McPherson (eds.), *Precipitation and Terrestrial Ecosystems*, John Hopkins University Press, Baltimore.

Hanson, P. J. 2000. Large-scale water manipulations. pp. 341–352. In O. E. Sala, R. B. Jackson, H. A. Mooney, and R. W. Howarth (eds.), *Methods in Ecosystem Science*, Springer-Verlag, New York.

Hanson, P. J., D. E. Todd, N. T. Edwards, and M. A. Huston. 1995. Field performance of the Walker Branch Throughfall Displacement Experiment. pp. 307–313. In A. Jenkins, R. C. Ferrier, and C. Kirby (eds.), *Ecosystem Manipulation Experiments: Scientific Approaches, Experimental Design and Relevant Results*, Ecosystem Research Report #20, Commission of the European Communities, Copenhagen.

Hanson, P. J., D. E. Todd, M. A. Huston, J. D. Joslin, J. Croker, and R. M. Augé. 1998. *Description and Field Performance of the Walker Branch Throughfall Displacement Experiment: 1993-1996,* ORNL/TM-13586, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Turner, R. S., P. J. Hanson, M. A. Huston, C. T. Garten, Jr., and P. J. Mulholland. 1993. A large-scale throughfall manipulation experiment on Walker Branch Watershed. pp. 96–105. In L. Rasmussen, T. Brydges and P. Mathy (eds.), *Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems: Approach - Methodologies - Findings*, Commission of the European Communities, Copenhagen.

B. LONG-TERM RESPONSE PAPERS

Curtis, P. S., P. J. Hanson, P. Bolstad, C. Barford, J. C. Randolph, H. P. Schmid, and K. B. Wilson. Biometric and eddy-covariance based estimates of ecosystem carbon storage in five eastern North American deciduous forests. *Agricultural and Forest Meteorology* (submitted).

Hanson, P. J., D. E. Todd, and J. S. Amthor. 2001. A six-year study of sapling and large-tree growth and mortality responses to natural and induced variability in precipitation and throughfall. *Tree Physiology* 21:345–358.

Johnson, D. W., P. J. Hanson, and D. E. Todd. The effects of throughfall manipulation on soil solution chemistry and leaching in a deciduous forest. *Journal of Environmental Quality* (submitted).

Joslin, J. D., M. H. Wolfe, and P. J. Hanson. 2001. Factors controlling the timing of root elongation intensity in a mature upland oak stand. *Plant and Soil* 228:201–212.

Joslin, J. D., M. H. Wolfe, and P. J. Hanson. 2000. Effects of shifting water regimes on forest root systems. *New Phytologist* 147:117–129.

C. PROCESS STUDIES

Augé, R. M, C. D. Green, A. J. W. Stodola, A. M. Saxton, J. B. Olinick, and R. M. Evans. 2000. Correlations of stomatal conductance with hydraulic and chemical factors in several deciduous tree species in a natural habitat. *New Phytologist* 145:483–500.

Augé, R. M, X. Duan, J. L. Croker, W. T. Witte, and C. D. Green. 1998. Foliar dehydration tolerance of twelve deciduous tree species. *Journal of Experimental Botany* 49:753–759.

Augé, R. M., C. D. Green, J. L. Croker, T. B. Johnson, A. J. W. Stodola, X. Duan, W. T. Witte, A. M. Saxton, R. M. Evans, J. B. Olinick, and P. J. Hanson. 1998. *Nonhydraulic signaling of soil drying and stomatal regulation in a forest ecosystem*. Final Technical Report, Southeast Regional Center, National Institute for Global Environmental Change. Environmental Institute Publication Number 66. The University of Alabama, Tuscaloosa.

Bruhn, J. N., J. A. Brenneman, J. J.Wetteroff, Jr., J. D. Mihail, and T. D. Leininger. 1997. Spatial patterns of *Armillaria* populations in the Walker Branch Watershed Throughfall Displacement Experiment, Tennessee, USA. pp 49–57. In S. G. Pallardy, R. A. Cecich, H. G. Garrett, and P. S. Johnson (eds.), *11th Central Hardwood Forest Conference.* U.S. Forest Service, Gen. Tech. Rep. NC-188.

Bruhn, J. N., J. J. Wetteroff, Jr., J. D. Mihail, J. M. Kabrick, and J. B. Pickens. 1998. Patterns of *Armillaria gallica*, *A. mellea*, and *A. tabescens* occurrence under field conditions. pp. 247–257. In C. Delatour, J. J. Guillaumin, B. Lung-Escarmant, and B. Marçais (eds.), *Root and Butt Rots of Forest Trees* (9th International Conference on Root and Butt Rots), INRA Editions (France), Les Colloques.

Chambers, L. S. 1998. *Characterization of forest floor carbon dioxide efflux from three forest ecosystems in East Tennessee, USA*. M.S. thesis. The University of Tennessee, Knoxville.

Croker J. L., W. T. Witte, and R. M. Augé. 1998. Stomatal sensitivity to nonhydraulic root to-shoot signals of partial soil drying in six temperate, deciduous forest trees. *Journal of Experimental Botany* 49:761–774.

Edwards, N. T., and P. J. Hanson. 1996. Stem respiration in a closed-canopy upland oak forest. *Tree Physiol*ogy 16:433–439.

Edwards, N. T., and S. D. Wullschleger. 2000. Carbon dioxide efflux rates from stems of mature *Quercus prinus* L. and *Acer rubrum* L. trees do not appear to be affected by sapflow rates. *Journal* *of Sustainable Forestry* 10:125–131.

Gebre, G. M., T. J. Tschaplinski, and T. L. Shirshac. 1998. Response in water relations of several hardwood species to throughfall manipulation in an upland oak forest during a wet year. *Tree Physiology* 18:299–305.

Gebre, G. M., and T. J. Tschaplinski. Solute accumulation of chestnut oak and dogwood leaves in response to throughfall manipulation of an upland oak forest. *Tree Physiology* (in preparation).

Holmgren, M. 1996. *Interactive effect of shade and drought on seedling growth and survival*. Ph.D. thesis. The University of Tennessee, Knoxville.

Holmgren, M. 2000. Combined effects of shade and drought on tulip poplar seedlings: Trade-off in tolerance or facilitation? *Oikos* 90:67–78.

Johnson, D. W., P. J. Hanson, D. E. Todd, R. B. Susfalk, and C. Trettin. 1998. Precipitation change and soil leaching: Field results and simulations from Walker Branch Watershed, Tennessee. *Water, Air and Soil Pollution* 105:251–262.

Johnson, T. B., R. M. Augé, C. D. Green, A. J. W. Stodola, J. B. Olinick, and A. M. Saxton. Correlations of stomatal conductance with hydraulic, chemical and environmental variables in five urban tree species. *Scientia Horticulturae* (in press).

Joslin, J. D., and M. H. Wolfe. 1998. Impacts of long-term water input manipulations on fine root production and mortality in mature hardwood forests. *Plant and Soil* 204:165–174.

Joslin, J. D., and M. H. Wolfe. 1999. Effects of minirhizotron installation disturbance upon root observation data. *Soil Science Society of America Journal* 63:218–221.

Shure, D. S., P. D. Mooreside, and S. M. Ogle. 1998. Rainfall effects on plant herbivore processes in an upland oak forest. *Ecology* 79:604–617.

Tschaplinski, T. J., G. M. Gebre, and T. L. Shirshac. 1998. Osmotic potential of several hardwood species as affected by manipulation of throughfall precipitation in an upland oak forest during a dry year. *Tree Physiology* 18:291–298.

Wilson, K. B., D. D. Baldocchi, and P. J. Hanson. Leaf age affects the seasonal pattern of photosynthetic capacity and net ecosystem exchange of carbon in a deciduous forest. *Plant, Cell and Environment* (in press).

Wilson, K. B., D. D. Baldocchi, and P. J. Hanson. 2000. Quantifying stomatal and non-stomatal limitations to carbon assimilation resulting from leaf aging and drought in mature deciduous tree species. *Tree Physiology* 20:787–797.

Wilson, K. B., D. D. Baldocchi, and P. J. Hanson. 2000. Spatial and seasonal variability of photosynthetic parameters and their relationship to leaf nitrogen in a deciduous forest. *Tree Physiology* 20:565–578.

Wilson, K. B., P. J. Hanson, and D. D. Baldocchi. 2000. Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle. *Agricultural and Forest Meteorology* 102:83–103.

Wilson, K. B., P. J. Hanson, P. J. Mulholland, D. D. Baldocchi, and S. D. Wullschleger. 2000. A comparison of methods for determining forest evapotranspiration and its components across scales: Sap-flow, soil water budget, eddy covariance, and catchment water balance. *Agricultural and Forest Meteorology* 106:153–168.

Wullschleger, S. D., and P. J. Hanson. 1996. Measuring stem water content in four deciduous hardwoods with a time-domain reflectometer. *Tree Physiology* 16:809–815.

Wullschleger, S. D., P. J. Hanson, and D. E. Todd. 2001. Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *Forest Ecology and Management* 143:205–213.

Wullschleger, S. D., and A. W. King. 2000. Radial variation in sap velocity as a function of stem diameter and sapwood thickness in yellow-poplar trees. *Tree Physiology* 20:511–518.

Wullschleger, S. D., K. B. Wilson, and P. J. Hanson. 2000. Environmental control of whole-plant transpiration, canopy conductance and estimates of the decoupling coefficient for large red maple trees. *Agricultural and Forest Meteorology* 104:157–168.

Wullschleger, S. D., P. J. Hanson, and T. J. Tschaplinski. 1998. Whole-plant water flux in understory red maple exposed to altered precipitation regimes. *Tree Physiology* 18:71–79.