ORNL/TM-13586

Environmental Sciences Division

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

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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

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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.

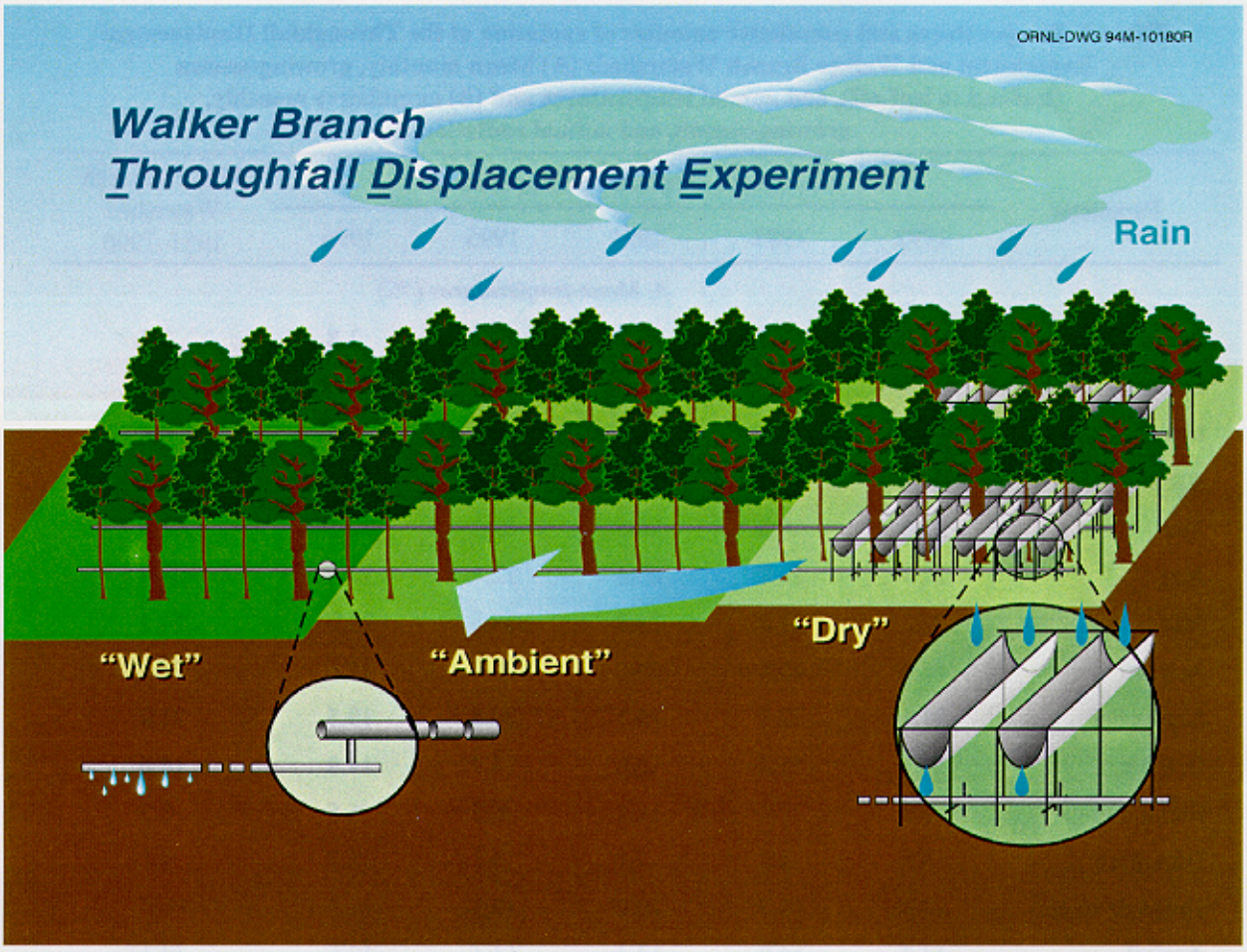

Fig. 1. Schematic diagram of the trough and piping network responsible for transporting ≈33% of total throughfall from the dry experimental plot across the ambient plot to distribution pipes extending the width of the wet plot. Each treatment plot was divided into an upper (rows 7–10), middle (rows 4–6),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

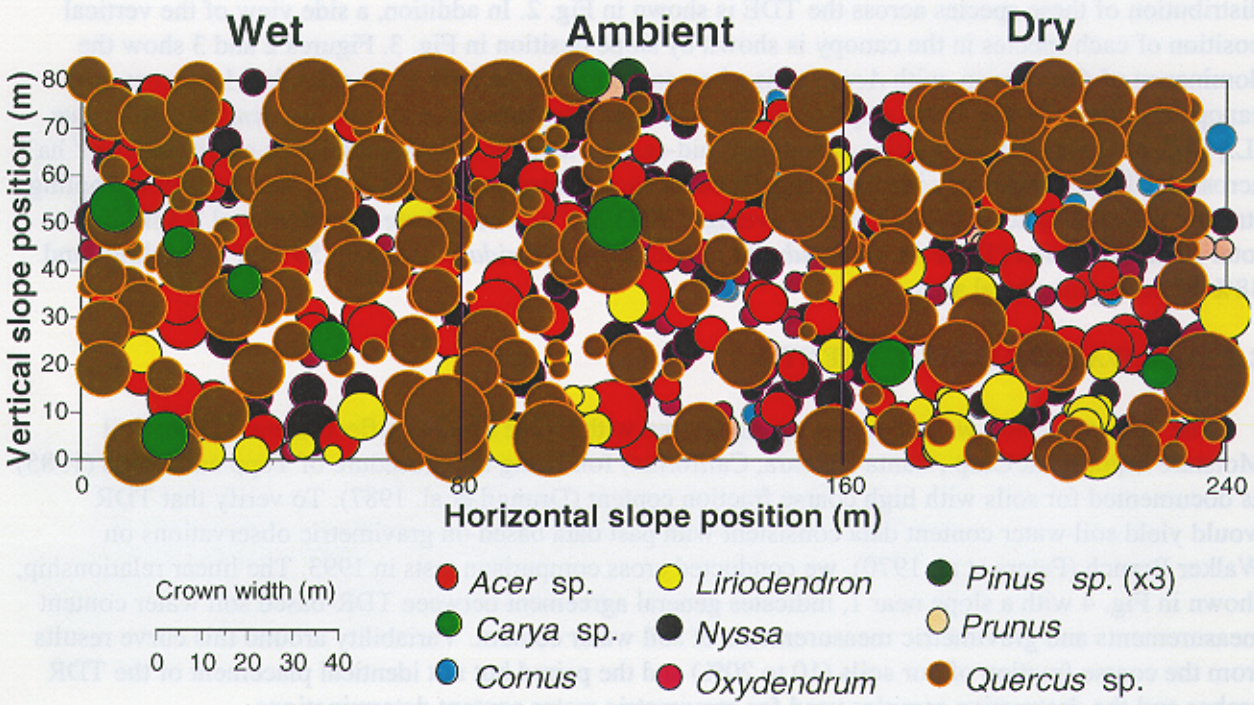

Fig. 2. An aerial view of the horizontal species distribution of all trees greater than 0.1 m in diameter at dbh across the Throughfall Displacement Experiment as of 1996. Circle size represents the canopy width of each tree. Top of the figure represents the top of the slope.

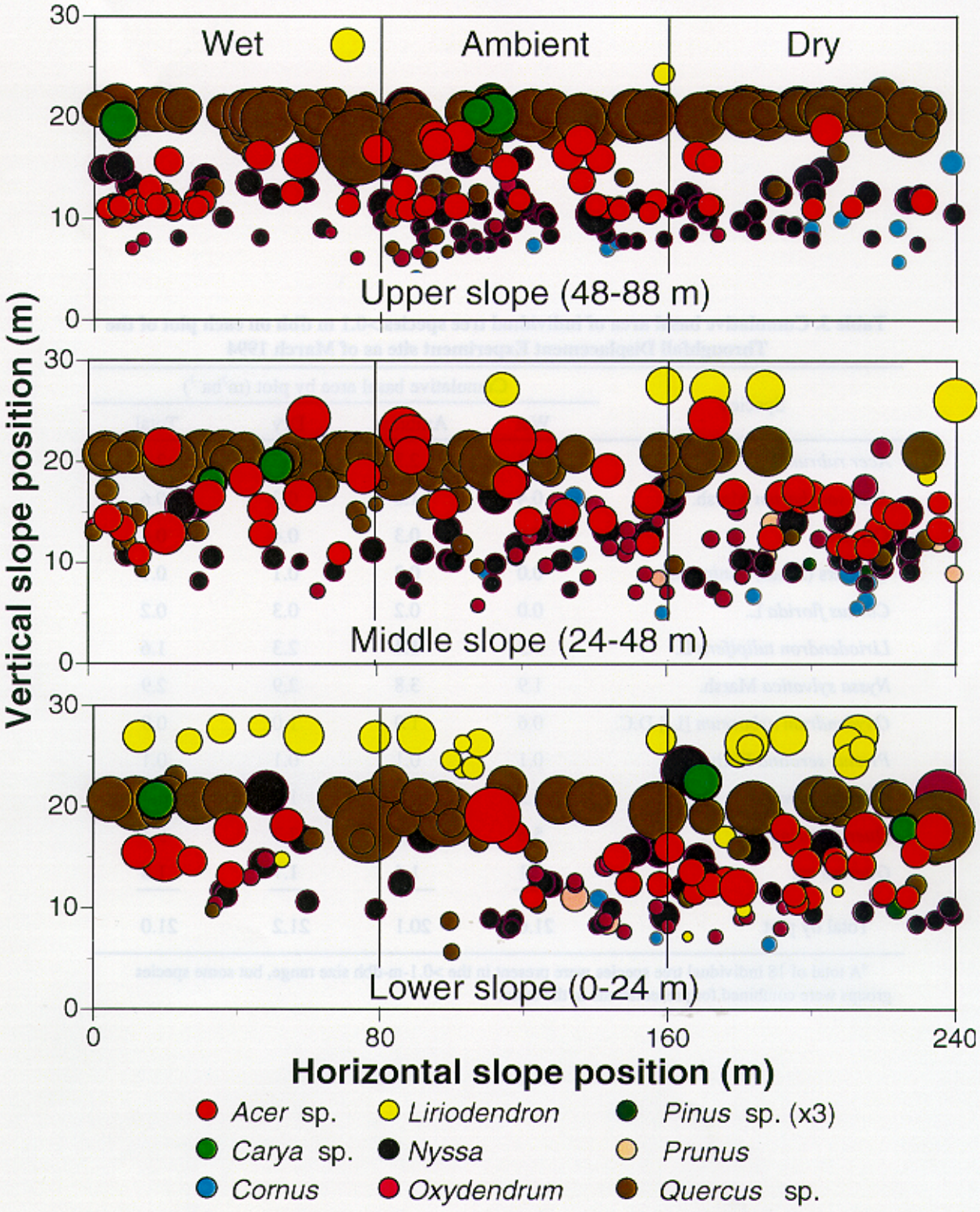

Fig. 3. A side view of the vertical position of individual tree crowns for (A) upper, (B) middle, and (C) lower slope positions across the Throughfall Displacement Experiment. Circle size represents the canopy width of each tree. Because this figure is based on trees greater than 0.1 m dbh few crowns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

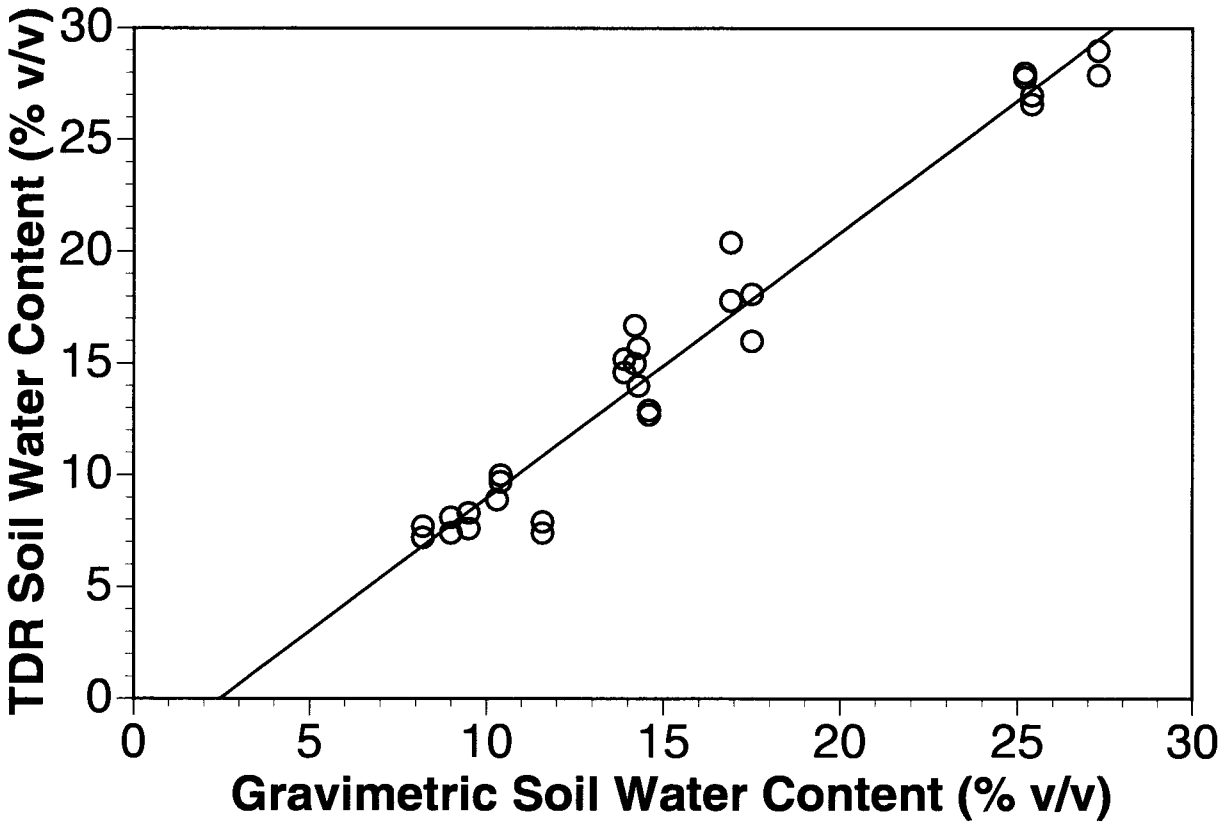

Fig. 4. Comparison of soil water content (v/v) obtained by means of time domain reflectometer and gravimetric approaches corrected for bulk density.

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:

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

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:

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

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.

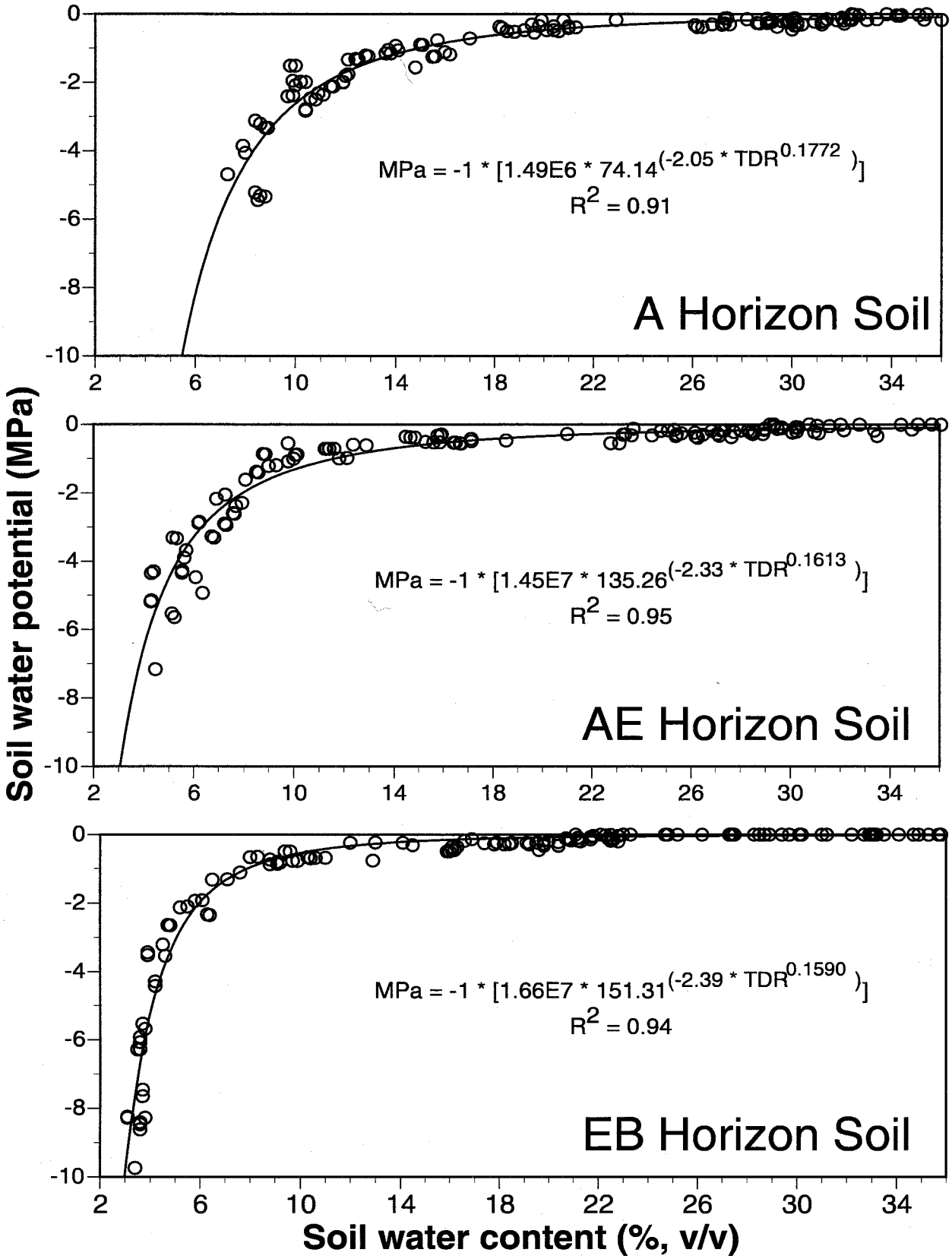

Fig. 5. Soil moisture release curves for representative A, AE, and EB horizon soils of the Throughfall Displacement Experiment. The fitted curves were generated with nonlinear least squares approaches.

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:

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

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

$$CovY_{ij} = (Y_{ij} - Y)/sdY , \tag{5}$$

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).

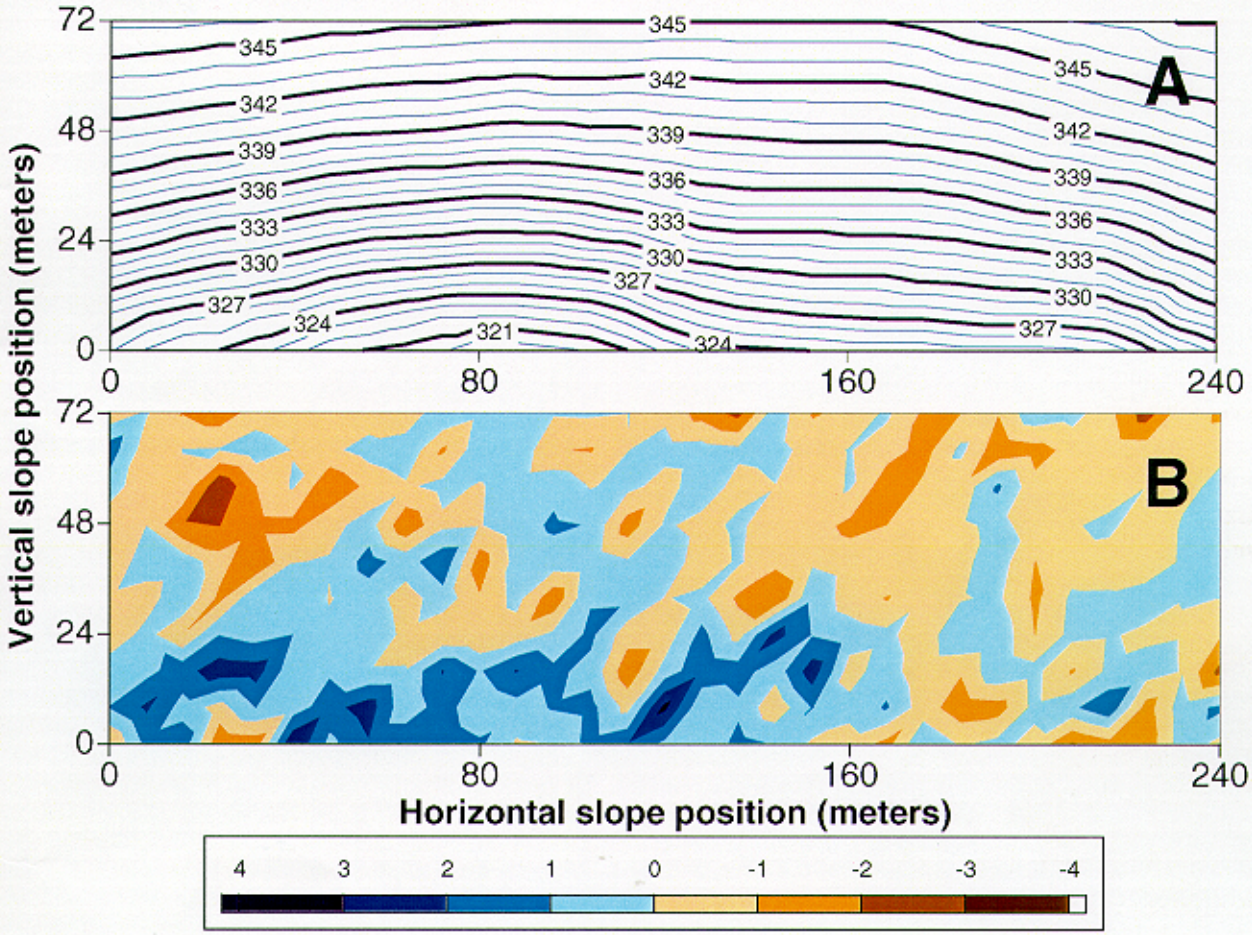

Fig. 6. (A) Elevation map of the experimental area in meters and (B) contour plot showing the pretreatment pattern of soil water across the experimental site expressed relative to the mean for the entire experimental area. A location with a rank of zero would be in agreement with the overall site mean.

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.

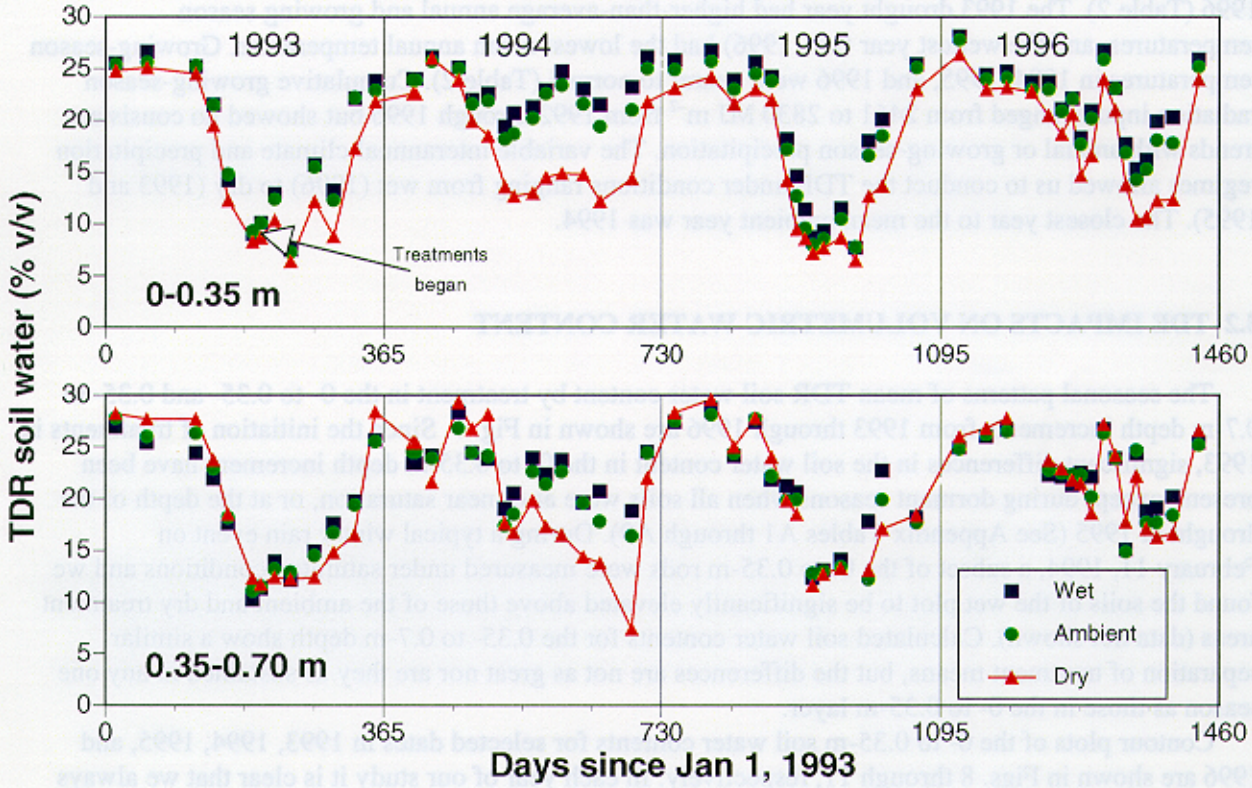

Fig. 7. The seasonal patterns of soil water content (% v/v) from 1993 through 1996 for the 0- to 0.35-m and the 0.35- to 0.7-m soil depths. Data are the mean values for the wet, ambient, and dry plots on the Walker Branch Throughfall Displacement Experiment. Throughfall displacement treatments were initiated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

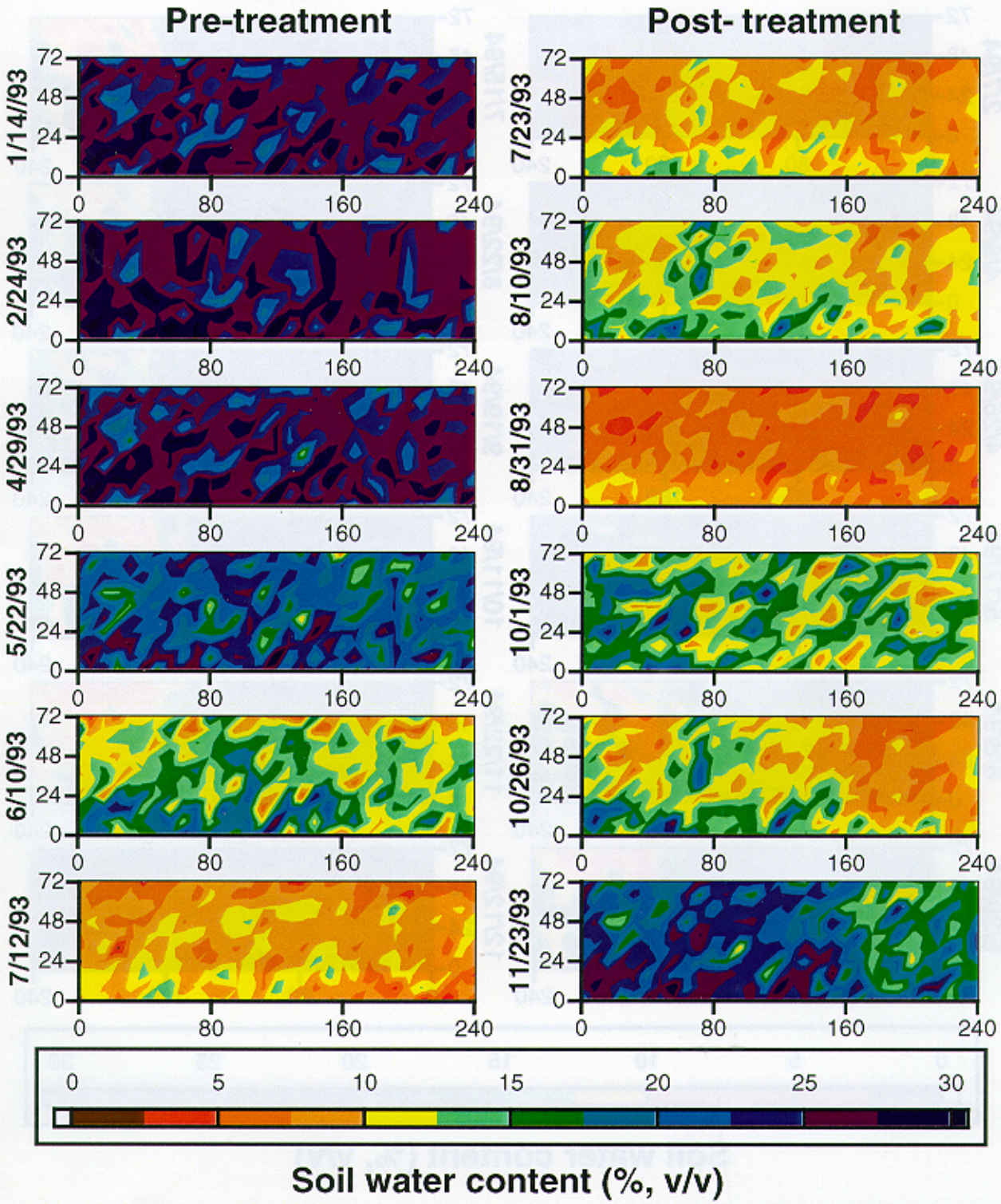

Fig. 8. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1993. Throughfall displacement was initiated between July 12 and July 23. Numbers along the x- and y-axis of each plot are meters.

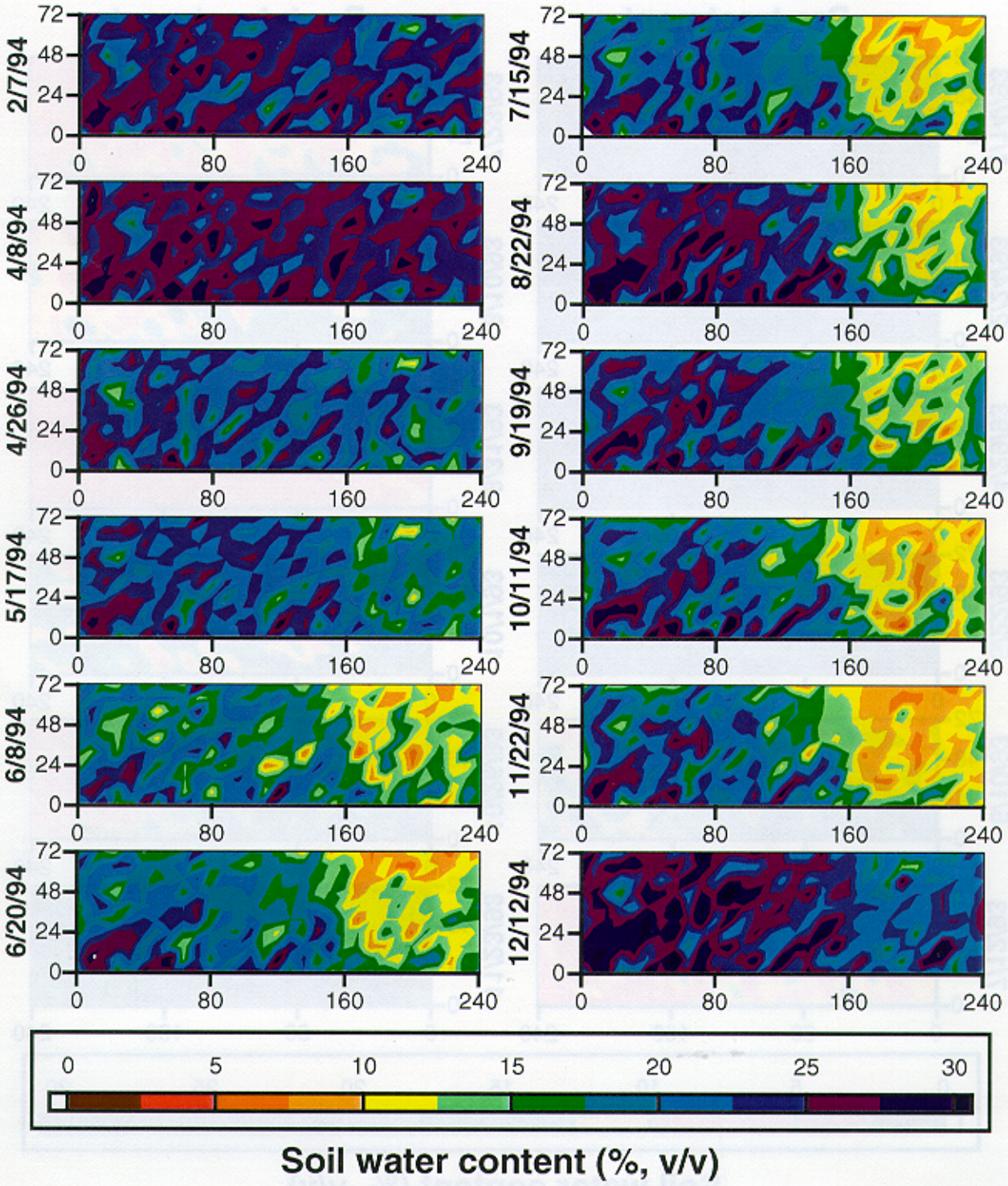

Fig. 9. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1994. March 4 and August 8 data were left off of this plot. Numbers along the x- and y-axis of each plot are meters.

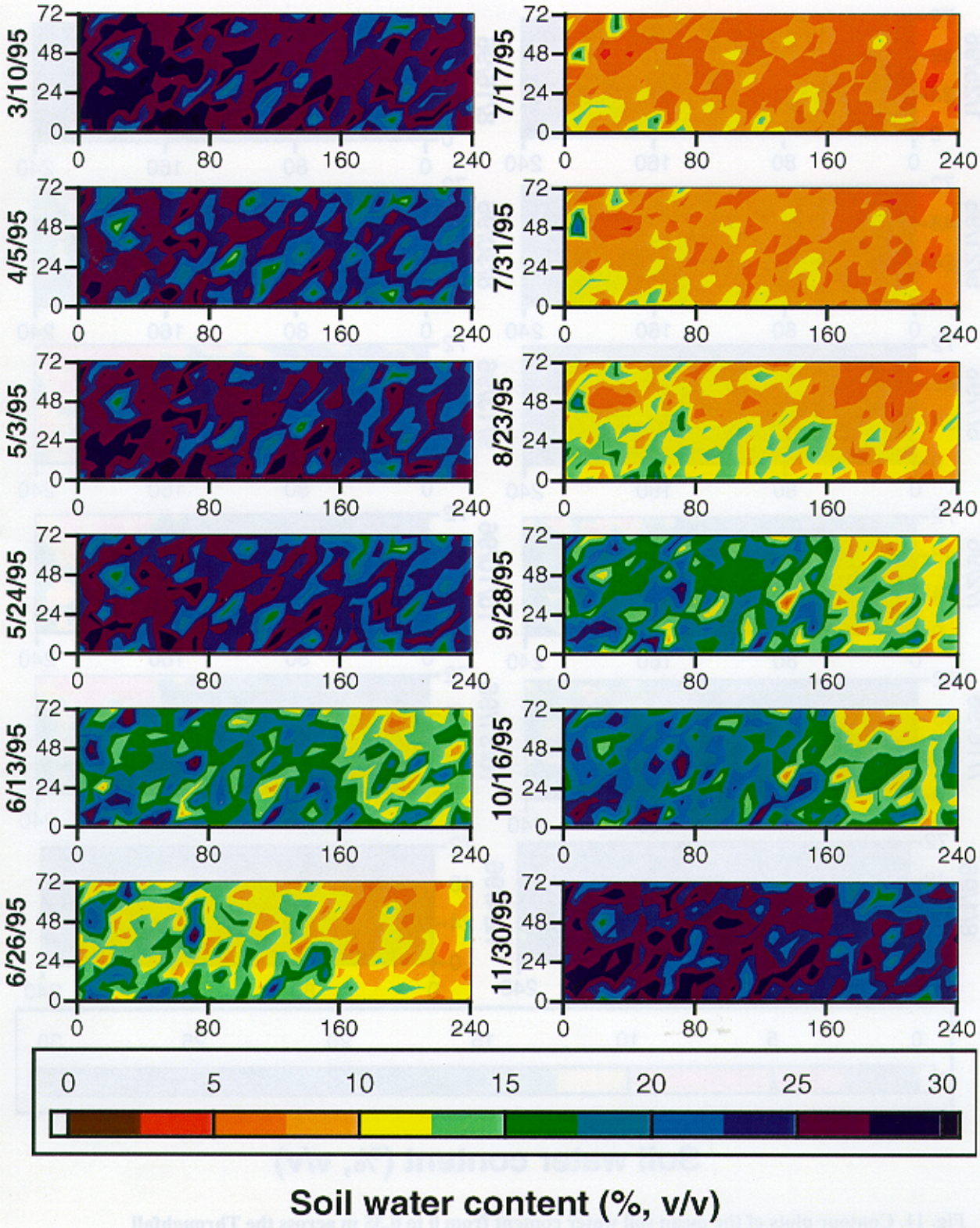

Fig. 10. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1995. The January 17 data were left off of the figure. Numbers along the x- and y-axis of each plot are meters.

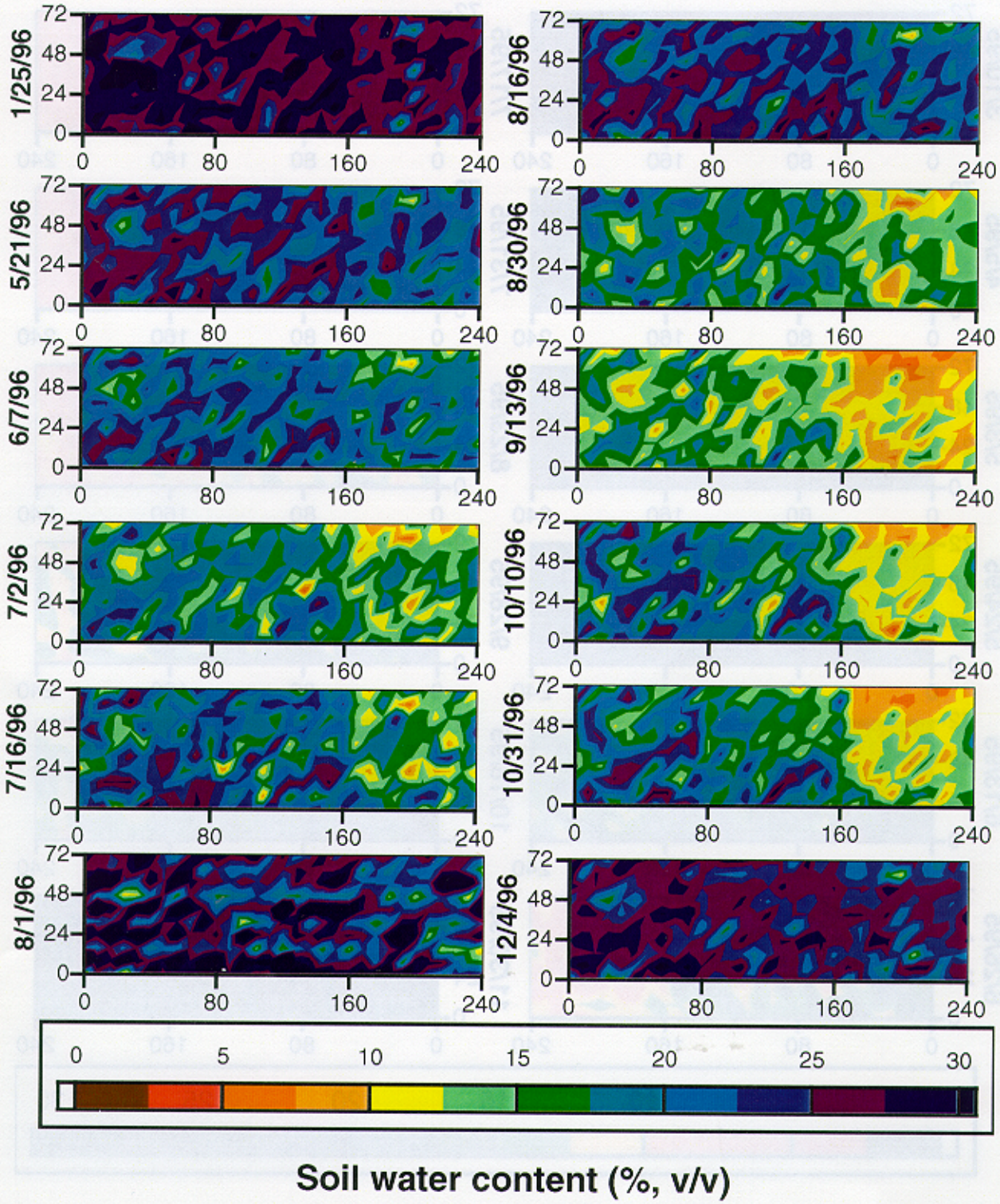

Fig. 11. Contour plots of the mean soil water content from 0 to 0.35 m across the Throughfall Displacement Experiment area throughout 1996. February 29, March 27, and April 29 data were left off of this plot. Numbers along the x- and y-axis of each plot are meters.

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.

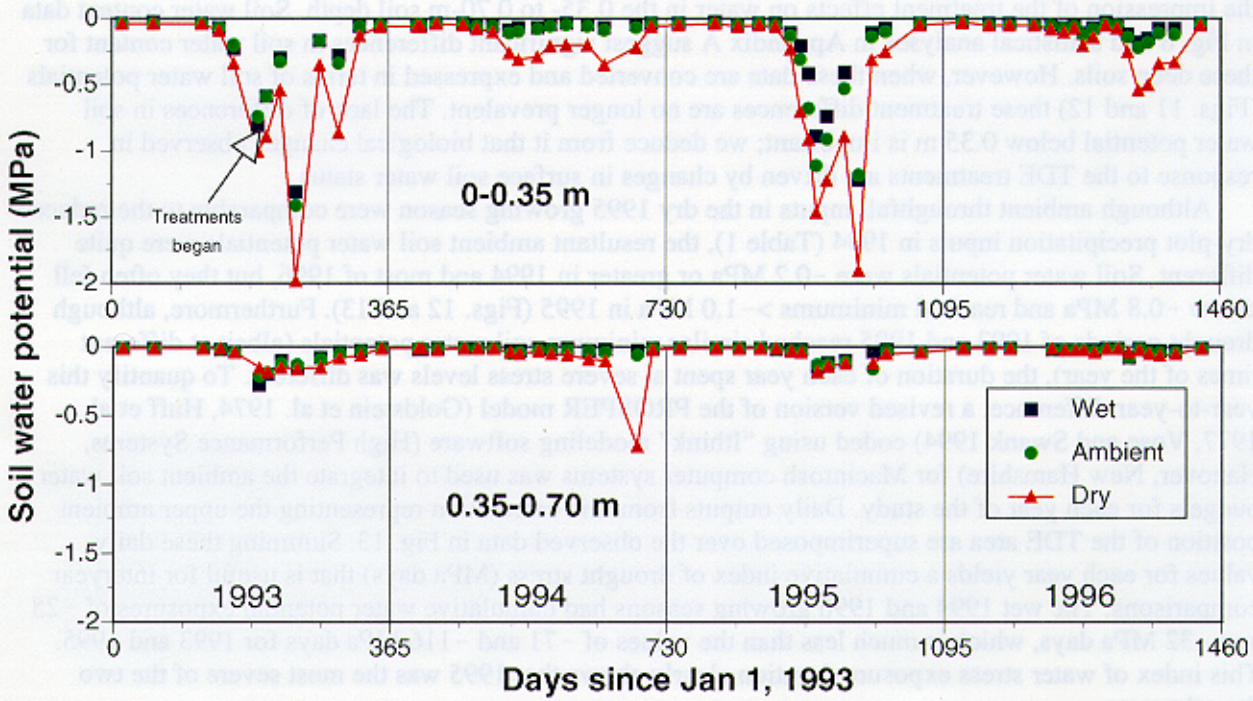

Fig. 12. Soil water potentials from 1993 through 1996 for the 0- to 0.35-m and the 0.35- to 0.7-m soil depths. Data are the mean values for the wet, ambient, and dry plots on the Walker Branch Throughfall Displacement Experiment. Throughfall displacement treatments were initiated on July 14, 1993 (see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

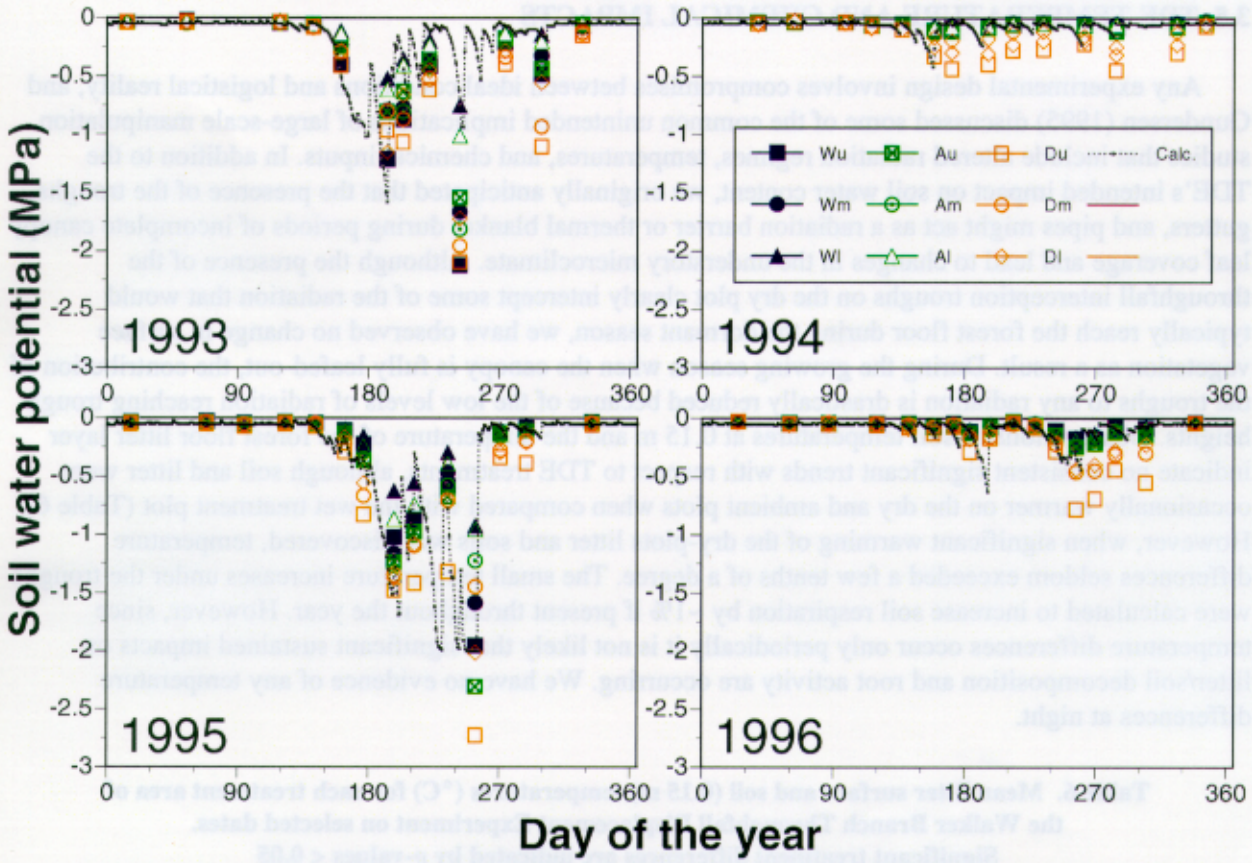

Fig. 13. Soil water potential for the 0- to 0.35-m depth for the nine treatment and slope positions of the Throughfall Displacement Experiment throughout 1993, 1994, 1995, and 1996. Soil water potentials were estimated from measured soil water contents and soil moisture release curves after correction 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 94	Dormant season			Growing season			Treatment
	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.

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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