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Field Performance of the Walker Branch Throughfall Displacement Experiment

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Summary - We are conducting a large-scale manipulative field experiments in an upland oak forest on the Walker Branch Watershed in eastern Tennessee USA to identify important ecosystem responses that might result from future precipitation changes. The manipulation of soil moisture is being implemented by a gravity-driven transfer of throughfall precipitation from one treatment plot to another. Throughfall is intercepted in ≈2000 subcanopy troughs (0.3 x 5 m) suspended above the forest floor of the "dry" plots (≈33% of the ground area is covered) and transferred by gravity flow across an ambient plot for subsequent distribution onto the "wet" treatment plot. Percent soil water is being monitored 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 extremely dry and extremely wet conditions. Furthermore, comparisons of pre- and post-installation soil temperature measurements have documented the ability of the experimental design to produce these changes without changing the microclimate of the forest understory.

1. Introduction

Researchers predict that increasing levels of greenhouse gases in the atmosphere will cause a 3 to 5 °C increase in average global temperatures and alter regional levels of precipitation. Rind et al. (1990) have argued that the incidence of drought is likely to increase with a warming global climate. Forests throughout the United States would be particularly vulnerable to the precipitation changes, especially in the southern states, where evapotranspiration demand is high and is predicted to increase as temperatures rise. The actual directions and magnitude of expected changes in precipitation are highly uncertain and specific scenarios for regional climate change do not exist. Turner et al. (1992) discussed plans for a large-scale manipulative experiment to address this uncertainty. The Throughfall Displacement Experiment (TDE) has now been initiated and is underway at the Walker Branch Watershed near Oak Ridge Tennessee, USA. The goal of the TDE experiment is to develop a mechanistic understanding of how forest ecosystem organisms adjust to changes in precipitation inputs that result from a warming global climate. The study evaluates the impacts of above- and below-normal levels of precipitation with respect to plant, pest/pathogen, and microbial processes that drive carbon, water, and nutrient cycling budgets. This paper describes the field performance of the throughfall transfer system required to facilitate the large-scale manipulation of soil water content in a mature upland oak forest.

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2. Site description

The throughfall displacement system for the experiment 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. Mean annual precipitation is 140 cm and mean temperature is 13.3°C. The acidic forest soils (pH 3.5 to 4.6) at this site are primarily typic Paleudults. These ancient residual soils are very cherty, 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. Stand basal area averages 20 to 25 m^2 ha^{-1}. The site was chosen because of its uniform slope, consistent soils, and a reasonably uniform distribution of vegetation. The site is dominated by Quercus alba, Quercus prinus and Acer rubrum L. but it contains just under 20 tree species (Table 1). The plot was located at the upper divide of the watershed so that lateral flow of water into the soils at the top of the "dry" plot would not confound attempts to create a reduced soil water treatment. The plot was also chosen to have a southern aspect so that the impacts of the reduced moisture treatment would be increased. The past 25 years of research on the Walker Branch Watershed (Johnson and Van Hook 1989) provide an important reference data base against which to judge the outcomes of the our large-scale manipulation.

3. Experimental Design

The manipulations of throughfall levels reaching the forest floor are made with a system designed to passively transfer precipitation from one experimental plot to another (Figure 1). Throughfall precipitation is intercepted in ≈2000 subcanopy troughs (0.3 x 5 m) suspended above the forest floor of the "dry" plots (≈33% of the ground area is covered). The throughfall is then transferred by gravity flow across a ambient plot and distributed onto the "wet" treatment plot through paired drip holes spaced approximately 1 m apart. The troughs are arranged in 21 rows of ≈80 to 90 troughs. Although stemflow is expected to contribute from 10 to 20 % of the total precipitation reaching the forest floor in heavy rain events (highly dependent on season and storm dynamics), collection and transfer of stem flow was not included in the current design.

Each treatment plot is 80 x 80 m (size was limited by the amount of uniform space available along the slope) and divided into 100 plots that serve as the locations for repetitive, nondestructive measurements of soil and plant characteristics. Reductions in soil moisture anticipated from the experimental removal of 33% of the throughfall will be comparable to the driest growing season of the 1980's drought (Cook et al. 1988), which resulted in sapling mortality and reduced growth of some vegetation (Jones et al. 1993). The experimental design includes both a wet and a dry scenario because of the uncertainties in making long-term predictions of precipitation patterns. Boardwalks for foot traffic were constructed at the base of each throughfall transfer pipeline to minimize soil compaction and site vegetation disturbance resulting from our activities on site.

We are not replicating the experimental design at another set of plots because the experimental design is costly. Instead, we are relying 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. To provide information for those variables we extensively characterized the site topography, soils, soil water patterns, microclimate, and vegetation before setting up the throughfall displacement system.

4. Soil water and climate measurements

Percent soil water content is being 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). A total of 310 sampling locations across the experimental site have been installed for long-term monitoring and for evaluating the effectiveness of the throughfall displacement system. At each location two pairs of TDR waveguides were installed in a vertical orientation (0-35 and 0-70 cm), but only data for the 0-35 cm waveguides will be discussed here. The TDR soil water content measurements can be converted to soil matric potentials, after adjusting the percentages for the coarse fraction in these soils, using moisture retention curves generated for the A and B horizons of these Typic paleudult soils (Peters et al. 1970).

To test for microclimatic changes induced by the presence of the throughfall troughs on the "dry" plot, we have been conducting periodic measurements of forest floor surface temperatures and soil temperatures at a depth of 15 cm.

Forest floor surface temperatures are measured with an infrared thermometer (Everest Scientific, Inc., Fullerton, CA) with the emissivity set to 0.98. Soil temperatures at ≈10 and 35 cm are measured hourly with soil thermistors at 2 fixed locations on each treatment plot to develop a data base for modeling soil processes. To better judge the impact of the dry plot troughs on soil temperatures, four transects (1 upslope, 2 midslope, 1 downslope) across the treatment plots (31 observations per transect) were measured periodically throughout the 1994 growing season. These data were collected with a penetrating thermocouple capable of recording to the nearest ±0.1 °C (Model 450-AET Omega Engineering Inc., Stamford, CT).

Rainfall is being measured continuously at a clearing close to the TDE site to be used as a surrogate for "above-canopy" rain inputs, and throughfall quantity is being monitored with two tipping bucket rain gauges with ≈3 m extension troughs attached on each experimental plot. Because the throughfall displacement system transfers chemicals in addition to water from the "dry" to the "wet" treatment plots, three throughfall collectors (each constructed from two 3 m plastic extension gutters which drain into a 20 liter carboy) were placed on each treatment plot to sample the low-, mid-, and upper-slope positions of each plot. The chemistries of these throughfall samples are contrasted with samples of the transfer solutions collected and drained to the junction of the pipelines between the ambient and "wet" plots. Because of limited funds for chemical analysis, only selected rain events >1 cm are being saved for chemical analyses. The following analyses are being conducted for throughfall and transfer solutions: pH, soluble reactive P, total soluble P, NO3-, NH4+, total nitrogen, and a number of inorganic elements.

Additional climate, growth, and physiological measurements are being collected in conjunction with the Throughfall Displacement Experiment, but they will be described elsewhere.

5. Performance of the Experimental Design

The pretreatment observations of seasonal patterns of soil water content, initiated in April of 1992, suggested the presence of significant pretreatment patterns of soil moisture across the experimental area (data not shown). 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. Recognizing this discrepancy the eastern third was assigned the "dry" treatment. To effectively judge the effectiveness of the throughfall transfer system, these spatial patterns had 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. Although pretreatment positional differences across the site were maximal during dry periods and minimal in the dormant season they turned out to be consistent throughout the season. The consistent tendency with respect to soil water content at a specific topographic location was used to build a covariate matrix characterizing those locations having higher or lower soil water contents with respect to the overall site mean. This matrix has subsequently been used in an analysis of covariance to test the effectiveness of the throughfall displacement system to influence the soil water contents of the "wet" and "dry" treatment areas with respect to the ambient plot. Figure 2 shows the covariate adjusted mean soil water content for each treatment area from pretreatment periods in 1993 through the most recent measurements on September 19, 1994. The 1993 growing season was very dry, especially early in spring, and the entire experimental area dried to near the season's minimum before the treatments were initiated (≈day 200 in Figure 2). Nevertheless, during the period of rewetting following leaf fall in 1993 (days 250 to 350; Figure 2) the dry plot consistently showed lower soil water content. During the dormant season between 1993 and 1994 all soils resaturated and differences between treatment plots disappeared. However, during a typical winter rain event on February 11, 1994 a portion of the 0-35 cm 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 (day 407 in Figure 2).

The 1994 growing season was almost the opposite of 1993 with 45 percent more precipitation than the long term average over the period from April through July. Notwithstanding these high precipitation inputs the "dry" treatment plot performed admirably. Statistically significant ($p<0.05$) reductions in soil water content were apparent beginning April 26, 1994 and they were present throughout the 1994 growing season (Figures 2 and 3). Figure 3 shows the level of spatial heterogeneity present across the TDE site prior to the development of significant treatment effects (April 8) and during maximum soil moisture deficits for 1994 (June 20). Because precipitation inputs were so high during the early part of the 1994 growing season soil matric potentials did not fall below levels critical for plant physiological function in any of the treatment plots (data are not shown).

Although the throughfall displacement and the resulting modifications of soil water are clearly the primary result of the experimental system, we originally hypothesized that the throughfall collection troughs might act as a radiation barrier or thermal blanket during periods of incomplete canopy leaf coverage. Observations of soil temperatures at 15 cm (Figure 4) and the temperature of the forest floor litter layer (data not presented) have shown no effects on these characteristics, and it appears that the presence of the troughs in our closed canopy stand have little impact on the understory microclimate.

Like any experimental design, our treatments involve compromises between ideal conditions and logistical reality. In addition to water, 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 besides the water manipulation. Although our measurements of the differential chemical inputs into each of the three treatment plots are not complete at this time
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). We will continue to monitor the chemical content of the transferred throughfall to evaluate its fertilization potential.

6. Conclusion

The experimental system developed for the Throughfall Displacement Experiments climate change scenario of ±33 percent change in precipitation reaching the forest floor of an upland oak forest is working well. The system has been able to produce statistically significant differences in soil water content in years having both extremely dry and extremely wet conditions. Furthermore, the experimental design is able to produce these differences without measurable impacts on the understory microclimate.

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Table 1. Characteristics of the tree species >10 cm dbh on the Throughfall Displacement Experimental site as of March 1994. Presented according to their contribution to total stand basal area.

Species[1]	Basal area (m^2 ha^{-1})	Diameter (cm) mean	(range)	Stems (# ha^{-1})
Quercus prinus L.	5.7	34.6	(10.9 - 74.7)	51
Quercus alba L.	4.3	30.5	(9.3 - 73.5)	48
Nyssa sylvatica Marsh.	2.9	19.3	(9.2 - 49.8)	87
Acer rubrum L.	2.3	20.2	(9.3 - 54.2)	58
Quercus sp.	2.0	35.8	(9.9 - 66.9)	17
Liriodendron tulipifera L.	1.6	29.9	(10.6 - 46.1)	21
Oxydendrum arboreum [L.] D.C.	0.9	16.6	(9.5 - 51.6)	34
Acer saccharum Marsh.	0.7	29.7	(12.3 - 52)	8
Carya sp.	0.4	35.0	(26.4 - 48.5)	4
Cornus florida L.	0.2	13.1	(9.9 - 22.4)	12
Prunus serotina Ehrh.	0.1	15.1	(10.3 - 22.8)	6
Conifers (*Pinus* , *Juniperus*)	0.1	20.4	(12.1 - 41.2)	4

[1]A total of 18 individual tree species are present in the >10 cm dbh size range on the experimental site, but some groups were combined for presentations in the table.

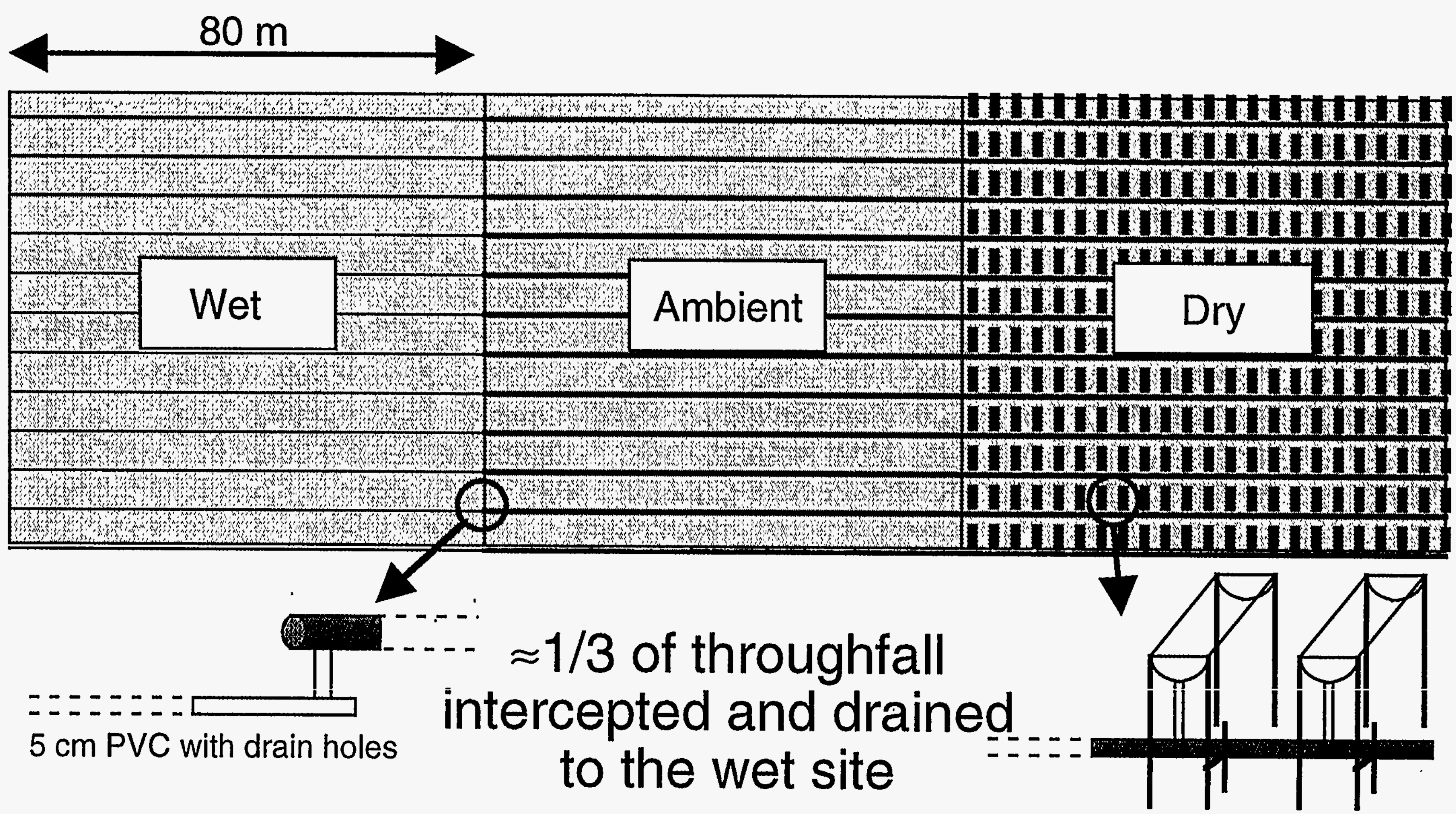
Figure Captions

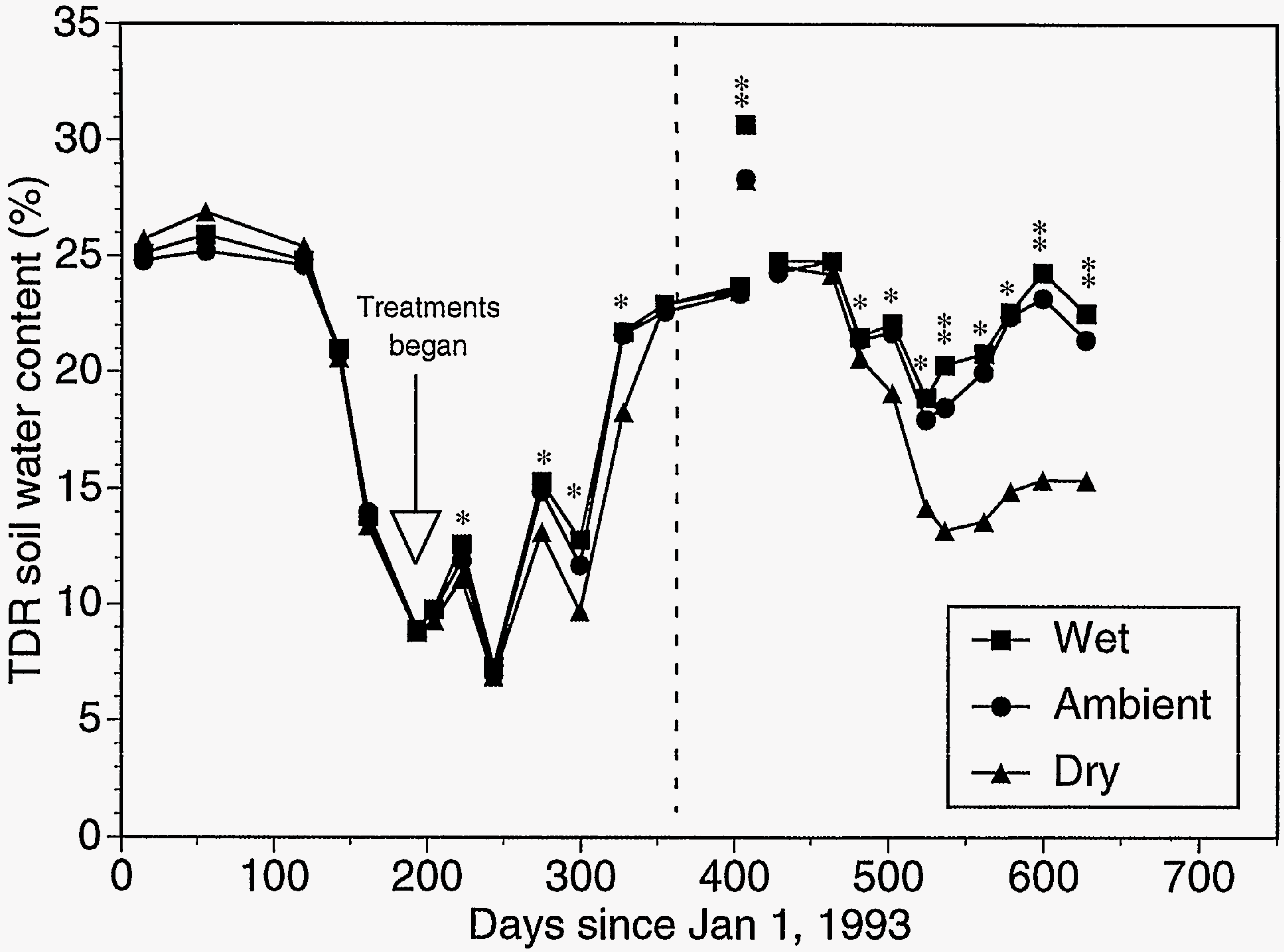
Figure 1. Schematic diagram of the trough and piping network responsible for transporting ≈33% of total throughfall from the "dry" experimental plot across the ambient plot to distribution pipes extending the width of the "wet" plot.

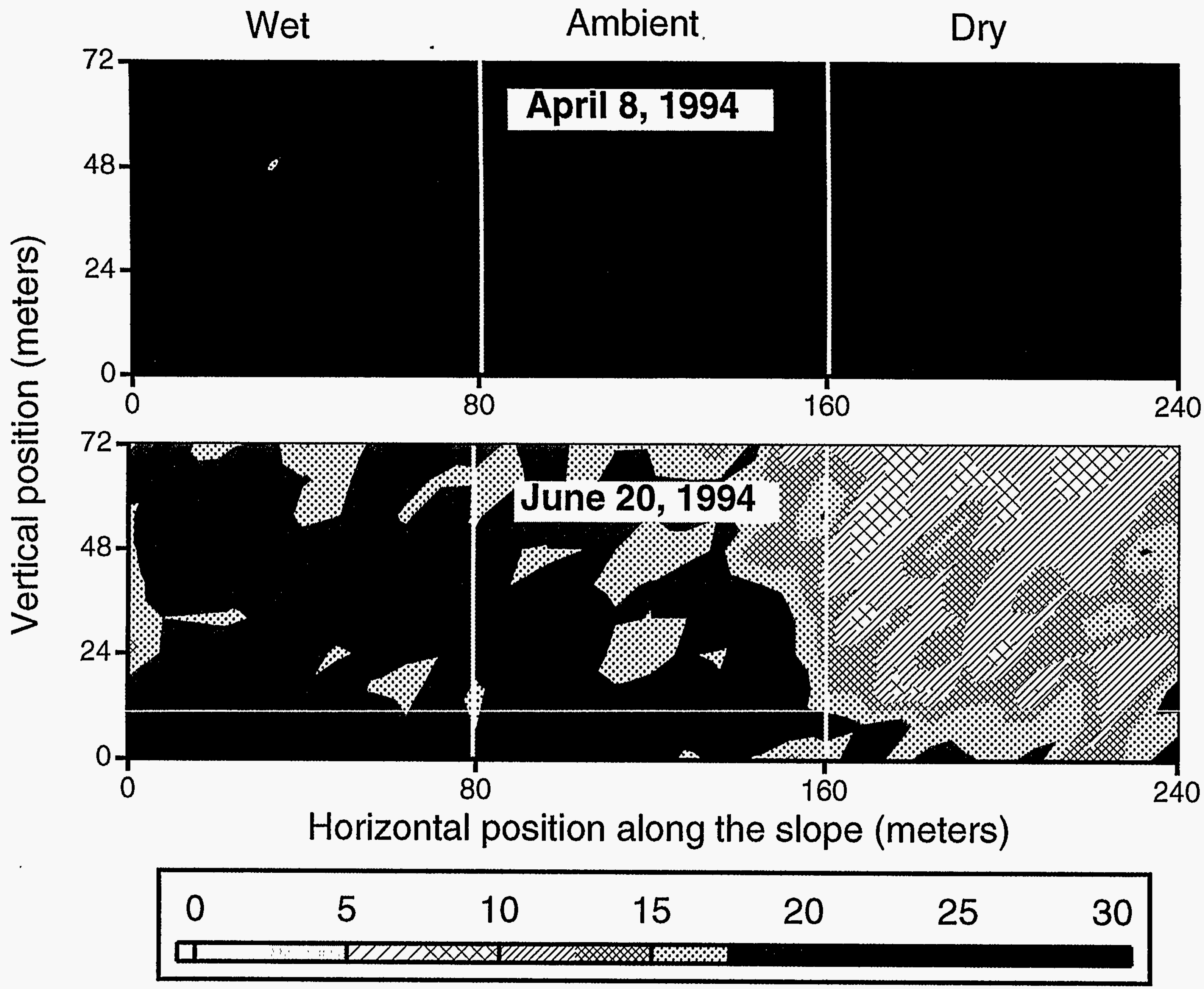
Figure 2. Mean soil water content from 0-35 cm measured by time domain reflectometry for the wet, ambient, and dry plots of the Throughfall Displacement Experiment. Treatments were initiated as shown by the arrow on the plot. Following the initiation of treatments, the presence of asterisks above a given date indicate a significant difference ($p < 0.05$) in the soil water content between treatments. '*' indicates the dry plot is different than the other treatments. '**' indicate that the wet plot is elevated above the ambient soil water content.

Figure 3. Spatial patterns of percent soil water content from 0-35 cm across the Throughfall Displacement Experiment site during periods of saturated soil conditions (April 8, 1994) and during summer drying (June 20, 1994)

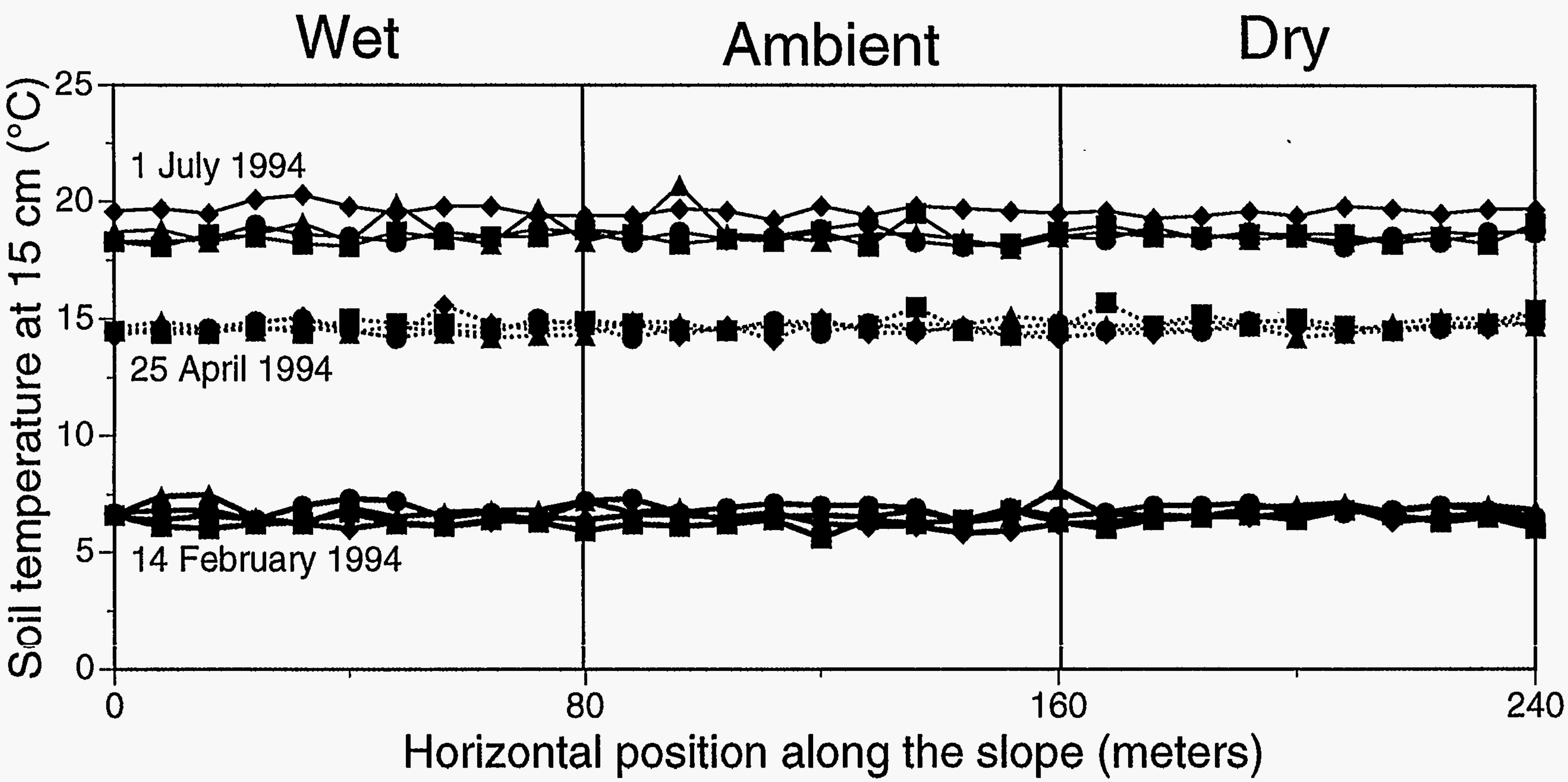
Figure 4. Soil temperatures at 15 cm depth across the experimental site for four transects representing upper (■), middle (● ▲), and lower (◆) slope positions. Data are shown for February 14, April 25, and July 1 of 1994.


80 m
Wet
Ambient
Dry
5 cm PVC with drain holes
≈1/3 of throughfall
intercepted and drained
to the wet site


35
30
25
20
15
10
5
0
TDR soil water content (%)
0
100
200
300
400
500
600
700
Days since Jan 1, 1993
Treatments began
Wet
Ambient
Dry



Wet
Ambient
Dry
April 8, 1994
June 20, 1994
Vertical position (meters)
72
48
24
0
0
80
160
240
Horizontal position along the slope (meters)
0
5
10
15
20
25
30


Wet
Ambient
Dry
1 July 1994
25 April 1994
14 February 1994
Soil temperature at 15 cm (°C)
25
20
15
10
5
0
0
80
160
240
Horizontal position along the slope (meters)