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Effect of Soil Type, Selected Best Management Practices, and Tillage on Atrazine and Alachlor Movement

EFFECT OF SOIL TYPE, SELECTED BEST MANAGEMENT PRACTICES, AND TILLAGE ON ATRAZINE AND ALACHLOR MOVEMENT THROUGH THE UNSATURATED ZONE

July 1, 1989 to December 31, 1991

Final Report

July 30, 1992

Wisconsin Groundwater Monitoring Program

Submitted To:

Wisconsin Department of Natural Resources
Bureau of Water Resources Management
Groundwater Management Section

Submitted By:

University of Wisconsin-Madison
College of Agricultural and Life Sciences
Department of Soil Science

Investigators:

Birl Lowery
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INTRODUCTION

Results from groundwater monitoring programs in Wisconsin have shown numerous cases of contamination by agricultural chemicals in areas with sandy soils and/or shallow aquifers (Postle, 1990). The extent and magnitude of this contamination, however, varies greatly between areas with similar landscape conditions and management practices. It appears that a particularly susceptible region is the intensively cropped, irrigated, sandy valley along the lower Wisconsin River (LWRV). Data from soil-column studies suggested that herbicide fluxes through the root zone of LWRV soils are 15 to 100 times greater than those through the similar, well-drained, sandy soils from the Central-Sands (CS) area of Wisconsin (Wietersen, 1991).

We need to understand the link between groundwater contamination and field use of agricultural chemicals in the LWRV, as well as the differences between sandy soils from the LWRV and CS. To address this need, in 1988, we (under the initial direction of Tommy Daniel) initiated a comprehensive study of herbicide and nitrate movement in the LWRV. The effects of soil type, irrigation management, tillage, and a tank mix polymer (that had been noted to reduce herbicide leaching) on agricultural chemical transport through the vadose zone to groundwater are being investigated. The primary goal of this research is to improve our understanding of the relationships between herbicide behavior and both intrinsic (i.e., inherent soil properties) and extrinsic (e.g., pesticide application and irrigation management strategies) variables.

PROJECT SYNOPSIS

The field site is located one mile north of the town of Arena in northeast Iowa County, and was established in June 1989. Core funding was provided by the Department of Agriculture, Trade and Consumer Protection, and the Department Natural Resources, together with, an allotment from the Nonpoint Source Pollution project, which is administered through the Department of Soil Science. Summer and fall of 1989 were devoted primarily to establishing tillage treatments and site characterization. Complimentary greenhouse and laboratory studies of herbicide leaching and adsorption were in progress.

The first full growing season in which herbicide and nitrogen application and monitoring were performed was 1990. Nitrate leaching measurements were added as a result of securing funds from the Wisconsin Fertilizer Research Council and the UW Groundwater Research Advisory Council. Instrumentation and sampling techniques were refined during the 1990 growing season. The 1991 growing season provided a second years data on herbicide and nitrate leaching.

Project activities have been carried out by various staff members, along with assistance from many cooperators (Table 1).

Table 1. Project staff* and cooperators, Lower Wisconsin River Valley Project, Arena, Wisconsin.

	Title	Area of interest
		Project Staff
Birl Lowery	Professor	Co-principal Investigator; water/solute movement
Kevin McSweeney	Associate Professor	Co-principal Investigator; site characterization
Kevin Fermanich	Associate Researcher	Project Coordinator
Dave Stoltenberg	Assistant Professor (Agronomy)	Co-investigator; *in situ* soil columns
Roger Springman**	Outreach Progr. Manager	Outreach/Education
Steve Grant**	Postdoctoral Researcher	Water and pesticide transport modeling
Rick Wietersen**	Grad. Research Assistant	Column leaching study
Brian Girard**	Grad. Research Assistant	Atrazine adsorption study
Cathy Seybold	Grad. Research Assistant	Soil characterization/mineralogy
Gary Hart**	Grad. Research Assistant	Field hydraulic properties
Dong Wang	Grad. Research Assistant	Preferential flow/ant ecology
John Norman	Professor	Preferential flow/ant ecology
		Field/Laboratory Support Staff
Brian Hess	Research Specialist	
Tom Reisdorf	Research Specialist	
Mike Pelech	Research Specialist	
Chris Johnson	Research Specialist	
		Cooperators
Jeff Postle	WDATCP, Agricultural Resource Management Division	
Dave Lindorff	WDNR, Bureau of Water Resources Management	
Homer LeBaron**	CIBA-GEIGY Corp., Agricultural Division	
Charles Smith**	USDA, Cooperative State Research Service	
Gordon Chesters	Groundwater Research Advisory Council	
Dick Wolkowski	Wisconsin Fertilizer Research Council	
Fred Madison	Wisconsin Geological and Natural History Survey	
Will Bleam	Soil chemistry (atrazine adsorption mechanisms)	
Wayne Kussow	Soil fertility (nitrogen management)	
Tommy Daniel	University of Arkansas (Project Advisor)	
Larry Binning	Nutrient and Pest Management Program	
Bill Bland	UW-Extension, WISP Weather Station Network	
Don Hartung	Hartung Brothers Inc. (Land Operator/Manager)	
Randy Hartung		
Alfred Anding, Jr.	Landowner/Personal representative Anding Estate	

* Staff are members of the Dept. of Soil Science unless otherwise noted.

** No longer involved with project.

OBJECTIVES

The revised objectives of the project entitled "Effect of soil type, selected best-management practices, and tillage on atrazine and alachlor movement through the unsaturated zone" were:

1. Track the movement of atrazine, alachlor, metolachlor, nitrate, and water through soil (Sparta sand) in the LWRV as a function of time.

2. Evaluate the effects of soil type (Plainfield vs. Sparta) on the transport of herbicide through the soil profile.

3. Evaluate the effects of such practices as irrigation scheduling and an experimental polymer on the movement of herbicide and nitrate.

4. Evaluate the effects of no-tillage vs. conventional (moldboard plow) tillage on the transport of herbicide and nitrate through the root zone.

5. Compare predicted vs. measured values (validation) of water, herbicide and nitrate movement through the soil profile using selected mathematical models.

Establishment of a field site in the LWRV was key to accomplishing the above objectives. A 2.8-ha (7-acre) field located north of Arena in Iowa County was selected as the research site in cooperation with Hartung Brothers, Inc. and Alfred Anding Jr. (Table 1). The site is representative of the intensively cropped and irrigated alluvial sands along the lower Wisconsin River.

This report summarizes results from the core project as well as allied studies of the soil type comparisons (objective 2). The soil type comparisons will be presented first, followed by results from measurements of field water and agrichemical movement (objective 1), and management effects (objectives 3 and 4).

EFFECTS OF SOIL TYPE ON HERBICIDE LEACHING

Three laboratory/greenhouse studies were conducted to determine the effects of soil type (primarily LWRV vs. CS soil) on herbicide transport:

1. Large-scale, long-term column leaching studies of herbicide transport;

2. Determination of atrazine adsorption coefficients on three soils;

3. Detailed chemical and mineralogical analysis of six Wisconsin sandy soils.

Column Leaching Study

During the period from July to December 1989 (156 days), a leaching study was conducted on 15 intact soil columns collected from the LWRV (Sparta sand, 12 columns) and the CS (Plainfield sand, three columns) area (Wietersen, 1991). The columns were 80 cm long and were operated under simulated field water (rainfall/drainage) and temperature regimes. Five treatments were studied: (1) irrigation of a Sparta sand to meet calculated evapotranspiration (ET) demand; (2) irrigation of a Plainfield sand to meet ET; (3) irrigation of Sparta columns to equal 1.5 inches of total water per week (ET+); (4) Sparta columns that received only simulated rainfall (no irrigation); and (5) same as treatment (1), but a poly-acrylate was added to the herbicide mixture. All columns received field recommended rates of atrazine (^{14}C-labeled), alachlor, and metolachlor.

Presented in Table 2 is total herbicide leachate loss after 156 days of simulated field conditions for the three compounds. Similar to a preliminary column study, there was a greater amount of atrazine leached from LWRV soil (Sparta) columns compared to the CS (Plainfield) columns. Very little alachlor leached from columns of either soil type or under any irrigation treatment. However, metolachlor exhibited similar behavior to atrazine, with significantly greater mobility in Sparta columns compared to Plainfield columns. Overall drainage from Plainfield columns was significantly less than Sparta columns, exhibiting water holding capacity differences between the soils. The three irrigation treatments of Sparta columns showed an increase in the amount of parent atrazine and metolachlor recovered in the leachate with increased water input. For all treatments, atrazine was the herbicide with the greatest mass recovered in the column effluent followed by metolachlor and alachlor, respectively (Fig. 1).

Leachate from Plainfield columns was comprised of primarily ^{14}C-metabolites of atrazine (2% parent atrazine) where as ^{14}C-atrazine residues in the effluent from Sparta columns was made up of 24 to 49% parent depending on irrigation. These results suggest a greater opportunity for degradation where less leaching occurred. The polymer treatment showed a significant decrease in the amount of metolachlor recovered in the leachate compared to the standard application. No conclusions were drawn with respect to the interaction of atrazine and the polymer because of problems encountered (dissolution) during application.

Atrazine Adsorption Study

Batch adsorption coefficients (K_d) of ^{14}C-labeled atrazine were determined for topsoil and subsoil of Sparta sand, Plainfield sand, and Plano silt loam at four concentrations and equilibration times (Girard, 1991). Properties of soil horizon samples used in the adsorption study are given in Table 3. Sparta samples from the LWRV were collected four miles west of the Arena field site, in the same area where soil columns were obtained. Table 4 presents data for the 24-hour equilibration time. Statistical analysis of the adsorption data from the batch experiments shows the topsoil of the Plainfield (CS) and Sparta (LWRV) soils are significantly different at the 99% level for all concentrations. For the subsoil (50 to 80 cm), the two sands

Table 2. Cumulative atrazine, alachlor, and metolachlor leachate loss from 80-cm columns of Central Sands (Plainfield) and Lower Wisconsin River Valley (Sparta) soils after 156 days of simulated field conditions (1989).

Treatment	Atrazine		Alachlor	Metolachlor			
	^{14}C*	Parent	Parent	Parent	Drainage	ET	Irrigation**
	% of applied				cm		
Plainfield ET	3.9(0.6)***	0.08(0.07)	0.008(0.004)	0.01(0.0003)	33.6(3.0)	29.4(4.3)	14.3
Sparta ET	14.5(9.9)	5.65(4.22)	0.011(0.010)	0.94(0.38)	44.3(3.8)	18.0(3.8)	14.3
Sparta ET+ 25%	15.7(5.8)	7.65(6.13)	0.013(0.009)	2.07(1.68)	47.7(3.8)	17.8(3.8)	18.1
Sparta No irrig.	5.7(3.0)	1.37(0.88)	0.010(0.006)	0.12(0.16)	30.4(2.6)	16.2(1.4)	0.1
Sparta w/poly ET	17.0(1.5)	4.21(0.43)	0.006(0.005)	0.04(0.02)	42.6(1.7)	19.2(0.9)	14.3

* Total ^{14}C-labeled atrazine residues (parent plus metabolites) leached from columns.

** All columns received 48.5 cm of water as simulated rain.

*** Mean of three columns (one standard deviation).

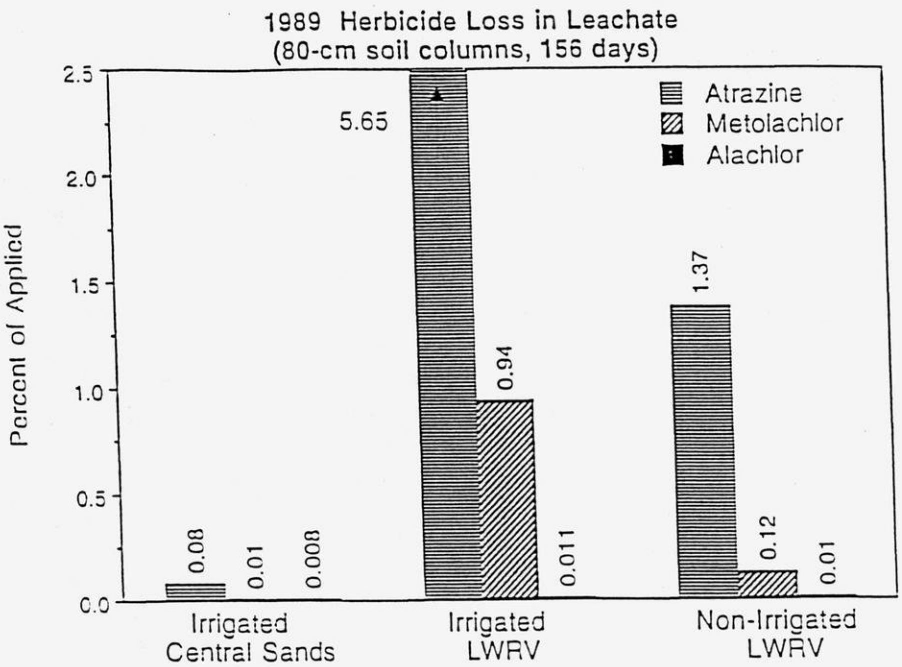


Figure 1. Herbicide-leaching losses from intact soil columns removed from Central-Sands region and the Lower Wisconsin River Valley.

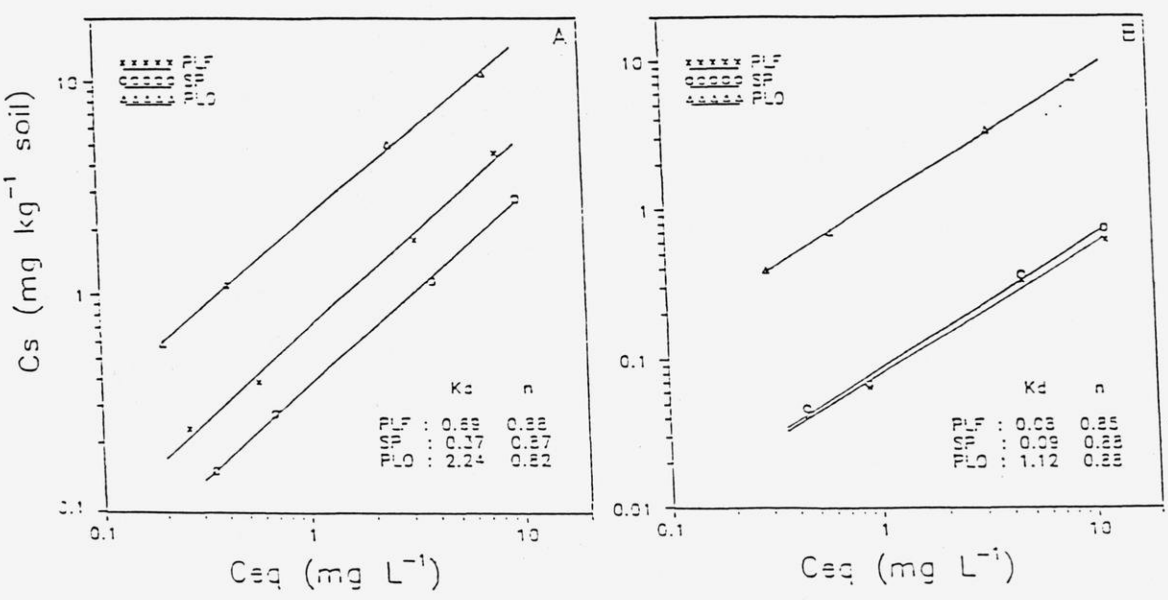


Figure 2. Atrazine adsorption (Kd) isotherms (24-hr equilibration) for Plainfield sand (PLF), Sparta sand (SP), and Plano silt loam (PLO). A is 0 to 20 cm depth. B is subsoil depth.

Table 3. Chemical and physical properties of soil samples where atrazine adsorption characteristics were determined.

Property	0 to 20 cm			50 to 80 cm		
	PLF*	SP	PLO	PLF	SP	PLO
Organic C (%)	0.46	0.37	2.14	0.07	0.15	0.64
Bulk density (g/cm^3)	1.65	1.67	1.26	1.69	1.61	1.21
Particle size (%)						
Sand	86.4	95.0	6.8	94.7	95.7	7.2
Silt	9.1	3.2	77.7	3.1	2.0	70.8
Clay	4.5	1.8	15.5	2.2	2.3	22.0
K_{sat} ($\times 10^{-5} m\ s^{-1}$)	2.25	11.8	0.10	11.2	10.3	0.10

* PLF = Plainfield sand, SP = Sparta sand, PLO = Plano silt loam.

Table 4. Atrazine adsorption (K_d) as a function of concentration after a 24-hour equilibration period.

Concentration	0 to 20 cm			50 to 80 cm		
	PLF*	SP	PLO	PLF	SP	PLO
mg/L						
0.5	0.89***	0.43	2.94	0.10	0.10	1.32
1.0	0.67***	0.40	2.68	0.07	0.08	1.14
5.0	0.55***	0.30	1.99	0.07	0.08	1.00
10.0	0.58**	0.29	1.51	0.05	0.06	0.86

* PLF = Plainfield sand, SP = Sparta sand, PLO = Plano sand.

, * Represent 95 and 99% confidence levels, respectively (comparing PLF to SP). At all concentrations the Plano soil was significantly different (99% level).

are not significantly different at the 95% level. Batch adsorption data were used to construct Freundlich sorption isotherms that are shown in Figure 2. As expected, atrazine adsorption was much greater in the silt loam soil.

Sandy Soil Characterization

Characterization of soil at the field site was conducted in 1989 and 1990. After establishment of the field site, six 25 ft by 6 ft by 6 ft trenches were made around the periphery of the tillage plots to provide access for soil characterization, classification, and sampling. Project personnel, along with members of the Soil Conservation Service (SCS) Soil Survey staff performed on-site, detailed soil profile descriptions of the north and south pits and collected samples for standard SCS laboratory characterization. Table 5 describes a typical profile at the site. Notable morphological features are open and filled channels throughout the soils, which are associated with the activities of ants and beetles. It was often noted that surface soil materials filled channels into the subsoil.

The extensive nature of these animal-derived "macropores" led to a USDA-CSRS-funded project aimed at understanding the relationship between these biopores and preferential movement of water and dissolved agrichemicals (Wang et al., 1991).

Objective 2 was expanded upon in a study entitled "Contamination attenuation indices for sandy soils: Tools for information transfer," which was designed to investigate the role that variation in intrinsic soil properties might play in affecting the fate of atrazine in a range of Wisconsin's sandy soils. Results from that study are summarized in detail in a report by McSweeney et al. (1991), which is included as an appendix to this report. A brief description of the study is presented here.

Five sandy soils, including one from the CS and LWRV, were selected to span a broad range of the variation in mineralogy, grain size, organic matter content and type, and geological origin found within the State of Wisconsin. The soils were analyzed to determine their chemical and mineralogical properties and to relate these to atrazine sorption. Variations in grain size distribution were also determined as a basis for making general interpretations about hydrological properties that might affect fate and transport of atrazine.

Estimates of secondary crystalline Fe-oxides and noncrystalline Fe- and Al-oxides did not significantly correlate with the adsorption coefficients of atrazine. No significant correlation resulted between the clay content, silt content and pH, and K_d values. The amount of organic carbon (% OC) was the most important constituent in terms of atrazine adsorption, the correlation coefficient (r) was 0.95. When the correlation was done by horizon, r increased to 0.98 for A horizons, and decreased to 0.85 for B horizons. Physical properties that affect rate and pathways of water movement differ among

Table 5. Profile description of a Sparta sand (Sandy, mixed, mesic Entic Hapludoll). This soil formed from sandy glacial outwash deposits on stream terraces, located in a cultivated field, in the Lower Wisconsin River Valley near Arena (about 1,300 ft. north and 1,100 ft. east of the southwest corner of Section 9, T.8N, R.5E).

Horizon	Depth (cm)	Description
Ap	0-23	Very dark brown (10YR 2/2) sand; weak medium subangular blocky parting to weak very fine granular structure; very friable; slightly acid (pH 6.4); abrupt smooth boundary.
A	23-33	Very dark brown (10YR 2/2) sand; weak medium subangular blocky structure; very friable; moderately acid (pH 6.0); clear wavy boundary.
AB	33-43	Dark brown (7.5YR 3/2) sand; weak medium and coarse subangular blocky structure; very friable; strongly acid (pH 5.4); clear wavy boundary.
Bw1	43-54	Strong brown (7.5YR 4/6) sand; weak medium and coarse subangular blocky structure; very friable; less than 1% gravel; strongly acid (pH 5.5); clear wavy boundary.
Bw2	54-66	Dark yellowish brown (10YR 4/6) sand; single grain; loose; less than 1% gravel; strongly acid (pH 5.3); clear wavy boundary.
BC	66-84	Yellowish brown (10YR 5/6) sand; single grain; loose; less than 1% gravel; moderately acid (pH 5.6); gradual wavy boundary.
CB	84-135	Brownish yellow (10YR 6/6) and light yellowish brown (10YR 6.4) sand; few fine and medium prominent strong brown (7.5YR 5/8) mottles; single grain; loose; less than 1% gravel; moderately acid (pH 5.7); gradual wavy boundary.
C	135-160	Pale brown (10YR 6/3) and very pale brown (10YR 7/3) sand; few fine and medium prominent strong brown (7.5YR 5/6) mottles; single grain; loose; about 3% gravel; moderately acid (pH 5.8); gradual wavy boundary.

the soils examined. These range from the LWRV soil (Sparta sand), which has a very uniform grain size (>96% sand) throughout the profile and no morphological evidence of hydrological discontinuities that might slow down water movement, to the CS soil (Plainfield sand), which has a much more variable grain size, including several gravel bands and presence of mottles that are indicative of impeded water flow. Impeded water flow may be expected to increase the contact time between atrazine and potential adsorption surfaces and thus reduce movement to groundwater. Although Sparta and Plainfield are both mapped in the CS and LWRV, these two regions differ appreciably in sources of materials (which affects mineralogy) and manner in which the materials were deposited (which affects grain size and occurrence of hydrological discontinuities).

Based on the three previously described studies, it appears that differences in herbicide leaching between the LWRV and CS areas are due, at least in part, to a combination of intrinsic factors. Because of uniform grain size distribution and lack of significant morphologic discontinuities in LWRV sand, water percolation is very rapid. Thus, solute-to-soil contact time is short. The water holding capacity of the LWRV sand is less than that of the CS soil. Generally, atrazine adsorption is slightly less in the LWRV soil. There is also indirect evidence, from the soil column study, that atrazine degradation may be faster in the CS, leading to less overall leaching. The processes of water movement, sorption, and degradation do not act independent of each other. Sorption and degradation in the unsaturated zone are directly linked to the rate of water movement through the root zone. The relationship between these processes appears to be unique for each of the soil types.

FIELD SITE METHODS AND MATERIALS

Hydrologic Properties of Sparta Sand

Quantification of the hydraulic properties associated with Sparta sand was achieved by *in-situ* monitoring of soil water characteristics under both irrigation and natural precipitation events occurring over the past 2 years. This monitoring exercise utilized the following equipment:

1. Weighing-bucket-style rain gages capable of measuring precipitation intensities ≥1 in/hr.

2. An automated time domain reflectometry (TDR) system (Baker and Allmaras, 1990) to monitor changes in soil water content throughout the profile over set time intervals.

3. Pressure-transducer-equipped tensiometers enabling measurement of soil water tensions at various depths.

4. Ceramic and stainless-steel porous cup samplers to monitor transport of a surface-applied bromide tracer.

A major portion of the data was collected with the time domain reflectometer. These data were used to quantify water flux (movement) through the vadose zone. Tensiometer data were used to establish profile hydraulic gradients and to construct the soil-water retention relationships at various depths. In addition, an instantaneous profile procedure (Watson, 1966; Hillel et al., 1972) was conducted in the fall of 1991 to assess the soils hydraulic conductivity. Because of the rapid drainage of the Sparta sand, data were collected via a computer from TDR and a datalogger for tensiometers at 15-minute intervals over the 6-month monitoring period. Hydrologic measurements were made in an area that was not vegetated.

A true "field capacity" water retention capability as proposed by Tanner (1990, personal communication) for sandy soils appears to have been observed for Sparta sand (Fig. 3). Under these conditions, the profile is in a pseudo-steady-state no-flow condition with respect to fluid water flow. This is substantiated by the drainage relationship shown in Figure 4. Water drains from a nearly saturated profile to field capacity within 1 day. By the end of 5 days, there was little or no drainage. The water content decreased from about 32.5% to about 11% in 3 days, with much of this occurring in 24 hr.

The rapid drainage combined with anion exclusion around soil particles may contribute to enhanced leaching potential of anionic chemical species.

The drainage curve obtained for Sparta sand displays water loss at an extremely high rate. Drainage data are also available for Plainfield sand in Central Wisconsin (Stoertz et al., 1991). The time frame at which drainage reaches asymptotic (constant) levels is quite similar for these two soils. However, Sparta sand reaches asymptotic water content values approaching half those observed for Plainfield sand at similar depths in the profile. Thus, the hydrologic nature of Sparta sand is considerably different than that of Plainfield sand. It may be theorized that percolation, drainage, hydraulic conductivity, and other hydrologic properties of interest should be measurably greater in Sparta sand.

The instantaneous profile procedure was used to gather information describing the drainage portion of the soil-water characteristic curve (Fig. 5) and the unsaturated hydraulic conductivity (Fig. 6). Soil-water tensions observed in Sparta sand are of low magnitude and have little impact upon the water flow regime. This creates a situation in which gravity is the major driving force for water flow, giving rise to high percolation and drainage rates. At comparable water contents for respective depths in the profile, Sparta sand has a one order magnitude larger hydraulic conductivity than that of Plainfield sand (Stoertz et al., 1991) (Fig. 7). Although this magnitude of variation may possibly be explained by experimental error (hydraulic conductivity data are generally considered ± one order magnitude), the observed differences in hydraulic conductivity support the contention that the hydrology of these two soils is significantly different, as alluded to in the previous paragraph. Additionally, research results regarding the lack of atrazine attenuation in Sparta sands (Girard, 1991; Wietersen, 1991) are in agreement with this disparity in hydraulic conductivity data for the two soils.

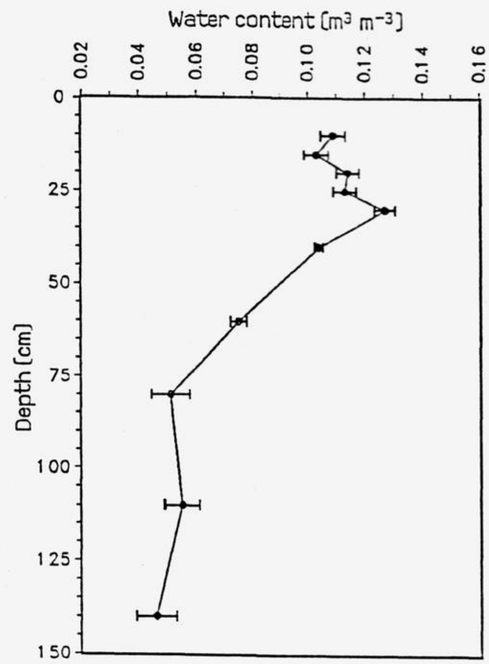


Figure 3. Observed "field capacity" water content through the Sparta sand profile (with evaporation). Error bars estimate +/- 1 standard deviation for the inherent error in the TDR system.

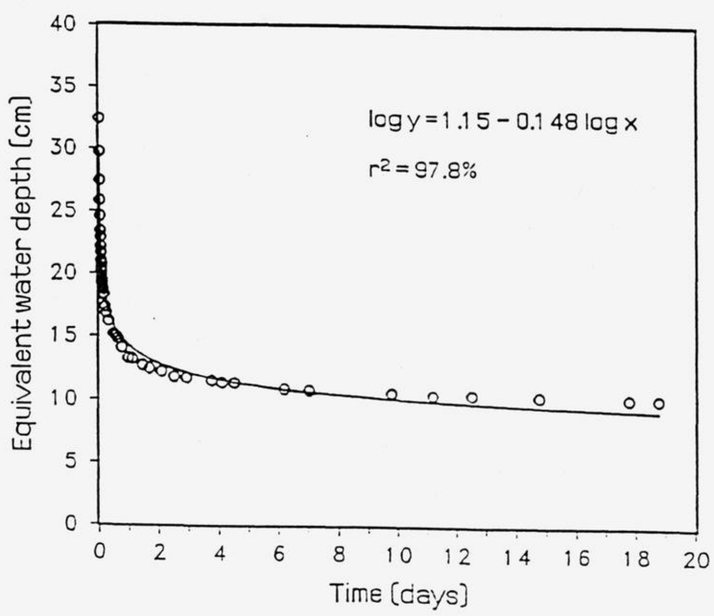
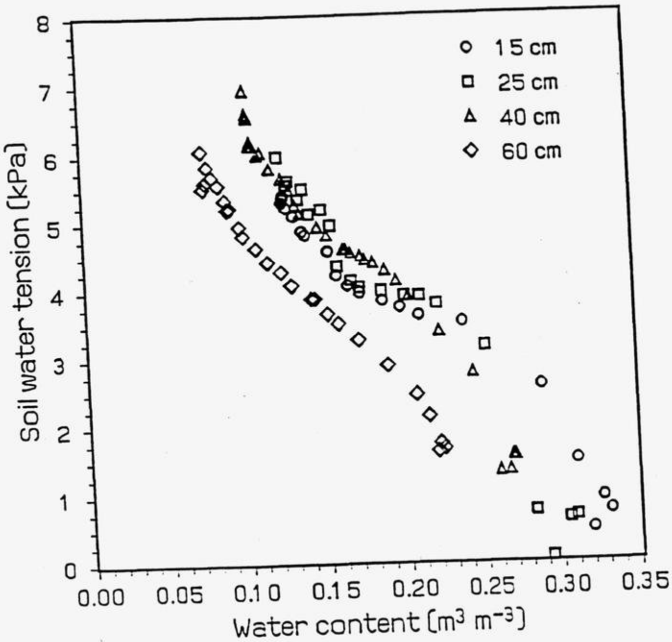


Figure 4. Drainage function for Sparta sand, with a monitored profile depth of 155 cm. Solid line represents best fit linear relationship.



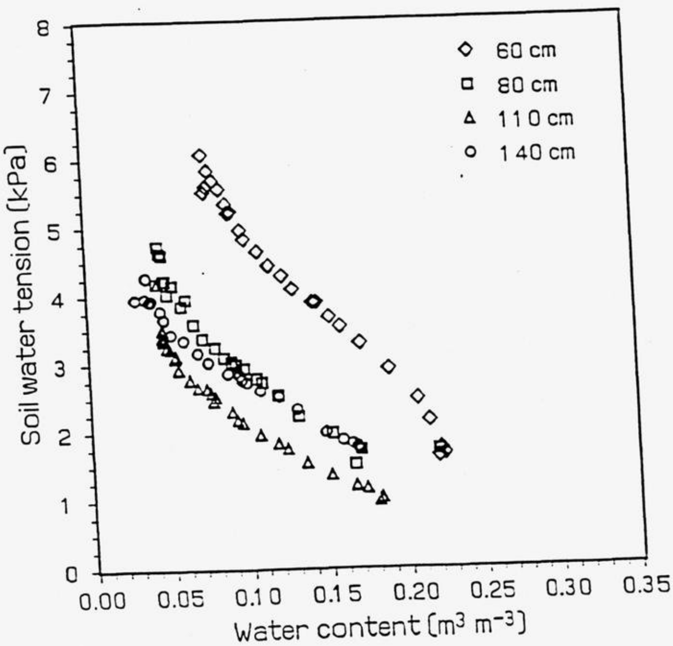


Figure 5. Soil water retention curves described by drainage in Sparta sand. Data points are mean values of two replicates for water content and tension at each depth shown. Data derived from *in-situ* monitoring during instantaneous profile procedure.

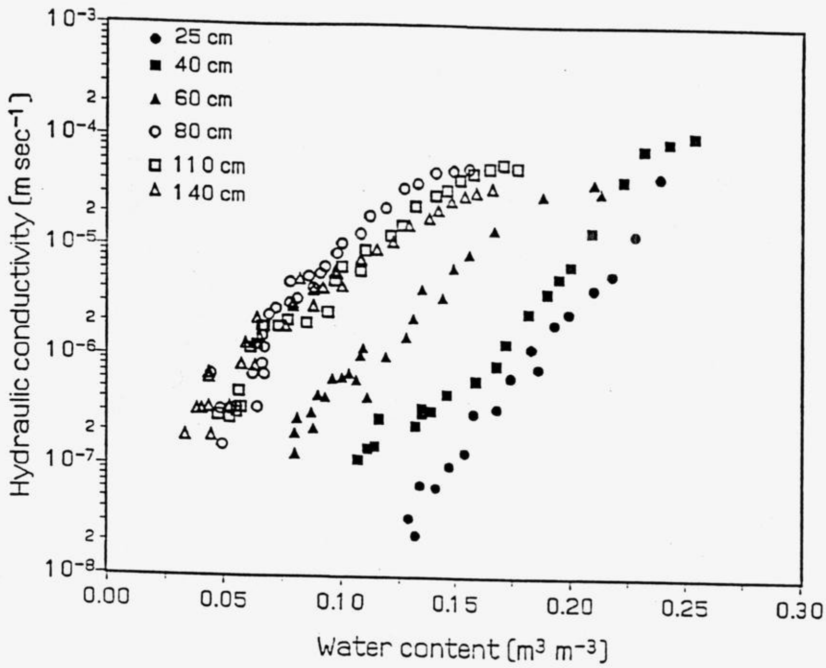


Figure 6. Hydraulic conductivity as a function of water content for monitored depths in Sparta sand.

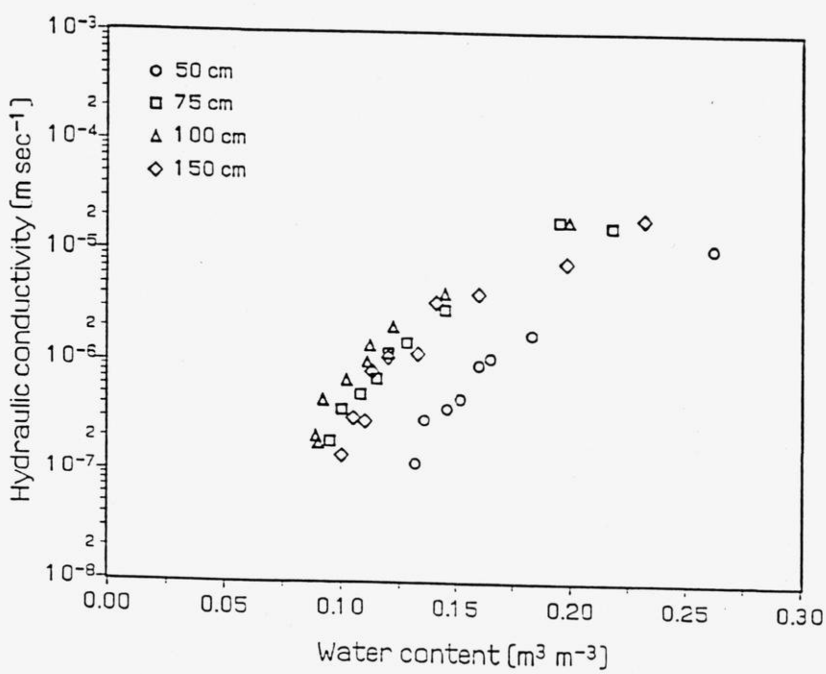


Figure 7. Hydraulic conductivity as a function of water content for various depths in Plainfield sand (Stoertz et al., 1991).

Following a 19-mm (0.75-inch) irrigation, wetting front movement was monitored with the TDR. Percolation data from eight replications were pooled and analyzed as a function of time. These data fit a log-log distribution of percolation depth and time, with $r^2 = 96.2\%$. This relationship was used to construct the graph presented in Figure 8, which depicts the rapidity of wetting front movement in Sparta sand.

Breakthrough curves for the bromide tracer were used to estimate the dispersion coefficient for bromide (Rose and Passioura, 1972) associated with anionic species under unsaturated flow conditions at Arena. This method results in the establishment of an apparent dispersion coefficient (Bond, 1987) through analysis of the temporal distribution of the breakthrough curves at various depths in the profile (Fig. 9). Symmetric breakthrough curves were obtained from the bromide tracer at all depths. The rate of solute movement in an unsaturated system is usually significantly smaller than the rate of movement of the moisture change for wetting front. This fact was observed for the bromide tracer experiment conducted at the Arena site.

Dispersion is often correlated in a positive manner with solute travel distance. However, in our experiment, dispersion decreased as travel distance (depth) increased. Similar results have been reported by other researchers (Wilson and Gelhar, 1981). This may be attributable to the heterogeneous nature of the Sparta sand profile and resulting variability in water flow and transport regimes with depth. Once a solute reaches the lower profile of Sparta sand, such phenomena may occur owing to (1) the rather low water content and resulting pendular saturation that exerts a physical barrier to diffusion, (2) a greater proportion of large pores and consequently lower pore water velocities and more uniform flow, resulting in less hydrodynamic dispersion, and (3) extremely high hydraulic conductivity so that when flow conditions are manifest they "plug flow." These factors may contribute to enhanced concentration levels of solute in the subsoil of Sparta sand.

The moisture regime associated with Sparta sand demonstrates little water holding capacity below 30 cm in the profile. Thus, we speculate that once contaminants reach depths greater than 30 cm, little attenuation is likely to occur due solely to the water flow regime and associated rapid transport. This phenomenon was demonstrated by the bromide breakthrough curves, in which bromide retention is shown to occur in the surface horizon, but not at depth. A comparison of transport velocities reveals that the bromide peak reached a depth of 140 cm over 15 times as rapid, on a relative basis, as that observed for a depth of 25 cm in the profile (Hart, 1992).

Site Layout and Treatments

A schematic plan of the field research site, showing 1991 experimental treatments and groundwater monitoring locations, is illustrated in Figure 10. The field experimental design was a split-split unbalanced block design. The main-block treatments were irrigation. The three irrigation treatments were: no-irrigation (No-I), irrigation to meet calculated evapotranspiration (ET)

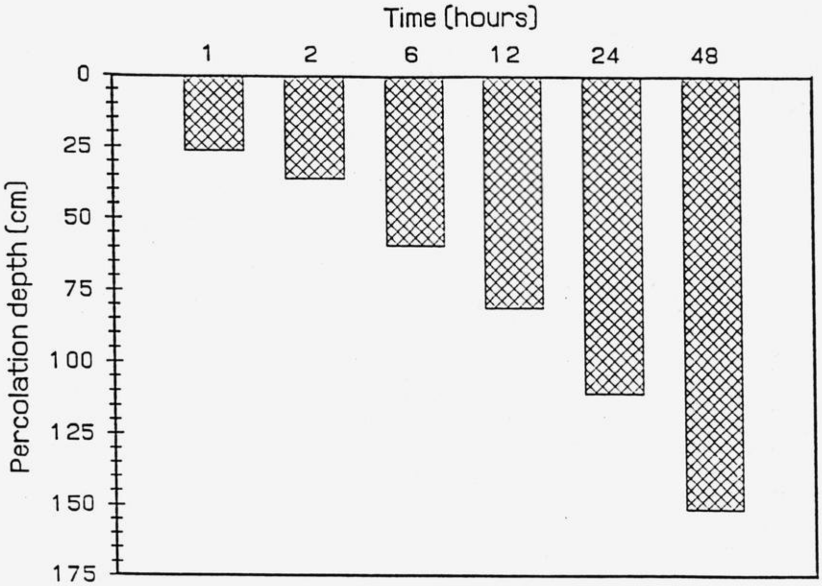


Figure 8. Percolation depth as a function of time, following 19mm irrigation water application.

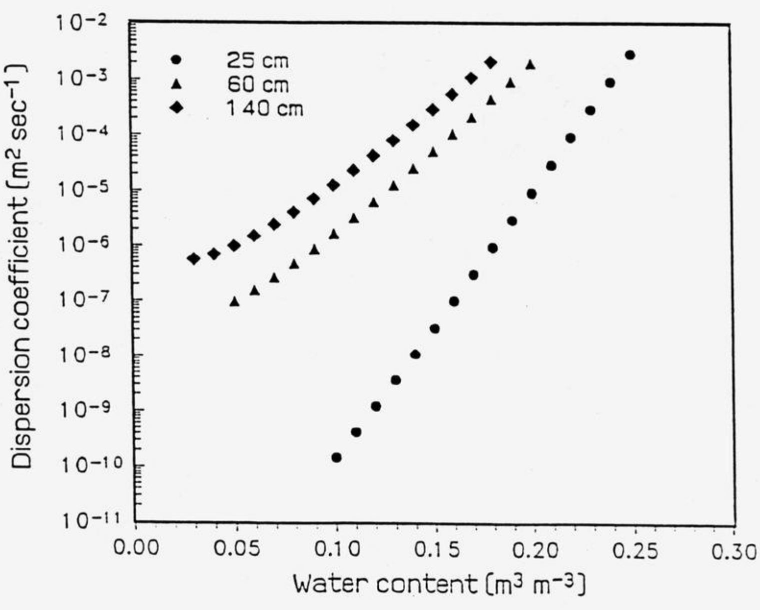
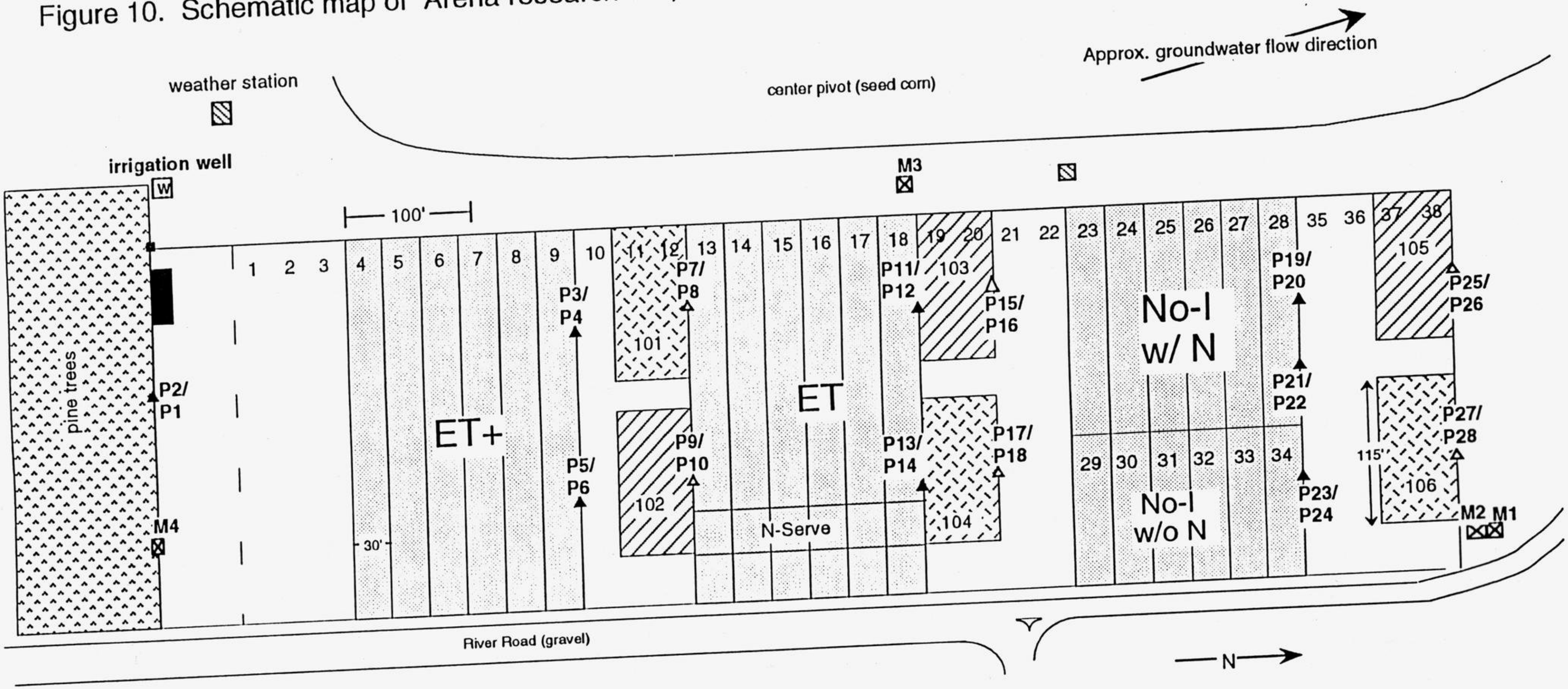


Figure 9. Dispersion coefficient estimates as a function of volumetric water content at three depths in Sparta sand. Data derived from temporal distribution of breakthrough curves for a bromide tracer at specified depths, along with time domain reflectometry water flux measurements.

Figure 10. Schematic map of Arena research site,1991.



Treatments

No-I	no supplemental irrigation
ET	irrigated to meet evapotranspiration water losses
ET +	irrigated to exceed ET water losses by 25 to 30%
MB	moldboard plow (conventional tillage)
NT	no-till (conservation tillage)

IRRIGATION RESEARCH PLOTS
CORN--MSEA
SOYBEANS--MSEA
Piezometer well--MSEA
Piezometer well--Irr. treatments
monitoring well

UW-Soil Science
11/26/91
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according to the Wisconsin Irrigation Scheduling Program (WISP), and irrigation to equal 1.5 inches (3.8 cm) of rainfall plus irrigation per week (ET+). The No-I block was split to give a control block with no-nitrogen under rainfed conditions. The sub-plot treatments were tillage: moldboard plow tillage (MB) and no-tillage (NT). Each tillage plot was split to accommodate a sub-sub-plot of with and without Acrysol ASE 108 polymer added to the herbicide tank mix.

The basic irrigation blocks and tillage sub-plots were the same for both the 1990 and 1991 growing seasons. However, six new plots were established in 1991 as part of a USDA-administered initiative on water quality in the form of Management System Evaluation Area (MSEA) plots. There are five main MSEA projects throughout the Midwest (they are located in Iowa, Minnesota, Missouri, Nebraska, and Ohio); the Arena site is a satellite of Minnesota's Northern Cornbelt Sand-Plain MSEA. The primary focus of all MSEA projects is to evaluate herbicide and nitrate leaching under ridge-till corn-soybean rotation. The herbicides (atrazine and metribuzin) were band applied over the row, resulting in one-third the normal broadcast area. The MSEA plots were irrigated the same as the regular ET block. Herbicide and nitrogen transport were monitored by soil coring and groundwater sampling. All soil samples were analyzed at the USDA National Soil Tilth Laboratory in Iowa.

In 1990, field plots were tilled and planted to corn (Pioneer 3578) on 29 April (day of year, DY 119). A starter fertilization of 100 lbs/A (112 kg/ha) 6-24-24 fertilizer and an application of 1.2 lbs active ingredient/A (1.34 kg/ha) terbufos (Counter) were made at planting. Herbicides were applied at recommended rates (Table 6) on 11 May (DY 131), following monitoring equipment installation. Acrysol ASE 108 was added to the herbicide tank-mix in the polymer treatments. Nitrogen fertilizer was applied as a side-dress of 190 lbs N/A (213 kg/ha) of 24-0-0 urea-ammonium nitrate (UAN) on 28 June 1990 (DY 179).

In 1991, field plots were tilled and planted (Pioneer 3417) on 3 May (DY 123). Starter fertilizer was applied at a rate of 82 lbs/A (92 kg/ha) 6-24-24 and insecticide (tefluthrin (Force)) at a rate of 0.15 lbs ai/A (0.168 kg/ha). Herbicides were broadcast applied after monitoring equipment installation on 8 May (DY 128) at the rates given in Table 6. Nitrogen fertilizer (24% UAN) was split applied on 7 June (DY 158) and 17 June (DY 168) at 86 lbs-N/A (96 kg N/ha) per application (total N equaled 172 lbs/A (193 kg/ha)).

Plots were irrigated with a three-tower, two-span, 313-ft-long linear irrigation system. Water was supplied to the irrigation system by a 60-ft-deep (18.3 m) supply well constructed at the site in April 1990. The well is fitted with a 230-gpm submersible pump. In 1990, the system was equipped with low-pressure spray nozzles located on top of the span pipes. This configuration was similar to that employed by growers in the valley. In 1991, the spray nozzles on top of the spans were replaced with drop tubes and nozzles with rotating spray-pads to give a more uniform spray pattern and to reduce wind effects.

Table 6. Herbicide application rates in 1990 and 1991.

Herbicide	No-polymer plots 1990	No-polymer plots 1991	Polymer plots* 1990	Polymer plots* 1991
	---------------- lbs ai/A			--------------
Atrazine (4L)	0.86	0.75	0.74**	0.81
Alachlor (Lasso, 4EC)	1.28	1.5	1.10	1.62
Metolachlor (Dual II, 8E)	1.28	1.5	1.10	1.62

* Acrysol ASE 108 polymer added to herbicide tank-mix [1.10 (1990 and 1.62 (1991) lbs of polymer solids per acre]. Buffered with $NaCO_3$ (1990) and NH_4OH (1991) to approximately pH 7.5.

** Rates for polymer treatment are less than regular treatment due to viscosity changes during application.

Water and Solute Monitoring

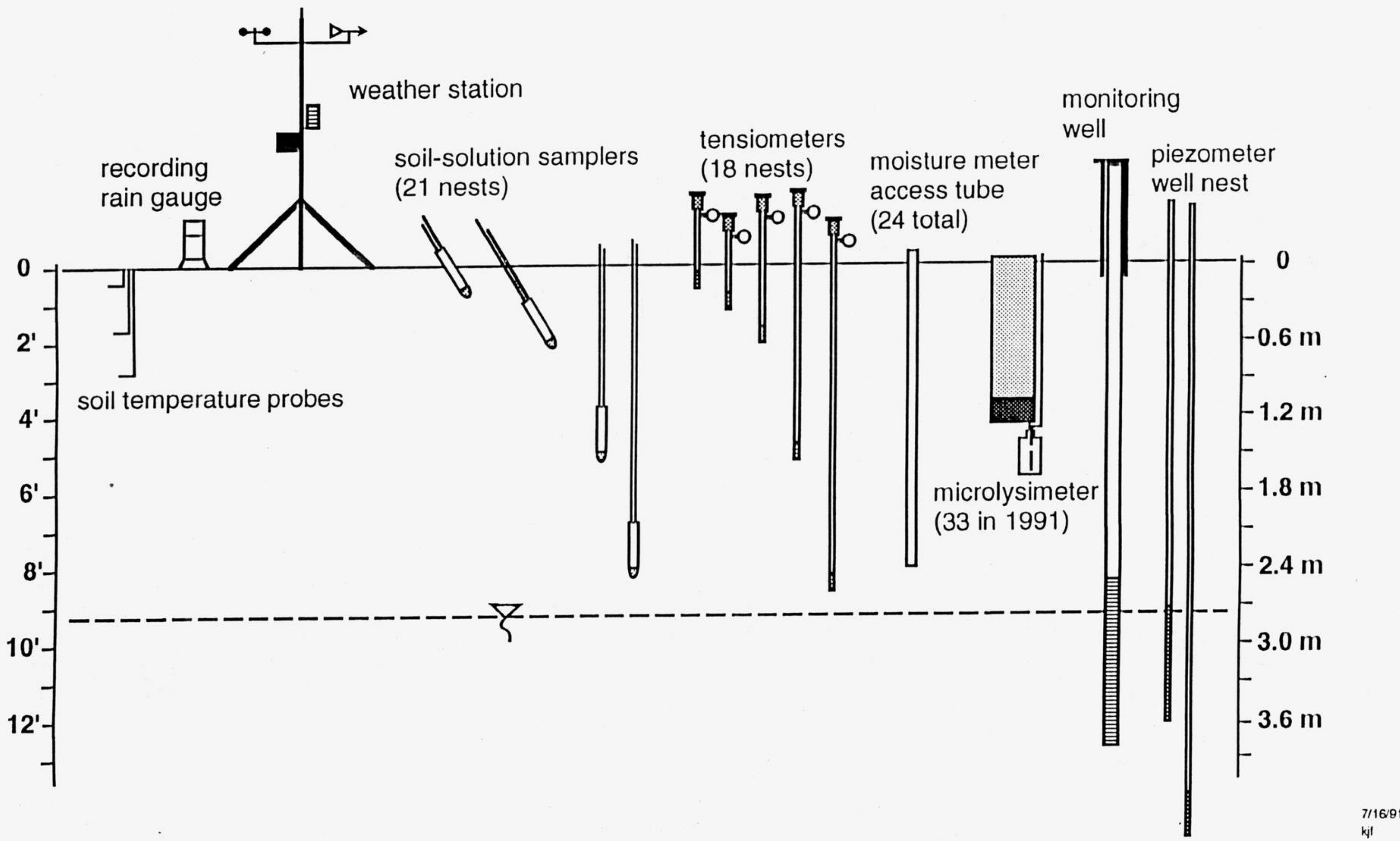
In cooperation with UW-Extension, a remotely-assessable, automatically-recording weather station was established adjacent to the research site in 1989. This station recorded the amount and intensity of rainfall at the site, as well as hourly air and soil temperature, relative humidity, solar radiation, wind speed and wind direction. These data were input into WISP to calculate ET and irrigation requirements. Project personnel recorded the quantity of water applied to each block as irrigation.

A schematic diagram illustrating the array of instrumentation at the field site is shown in Figure 11. All instrumentation requiring soil excavation for installation was installed during the period between planting and herbicide application each season to minimize contamination of the subsoil and samplers. Monitoring equipment was located in the western half of the tillage strips to maintain relatively undisturbed areas for following years.

Steel neutron-moisture-meter access tubes (200 cm by 4.2 id) were installed in each MB and NT tillage plot (24 in 1990, 21 in 1991). Soil-water content was determined weekly with a Campbell Pacific Nuclear Model 503 Hydroprobe in tubes in the ET irrigation block in 1990 and all tubes during 1991. Tubes in the ET+ and No-I blocks were measured bi-weekly in 1990. The moisture probe was calibrated for soil conditions at the site.

Herbicide and nitrate movement were monitored with a combination of porous-cup solution samplers (PCS), soil coring, and groundwater monitoring wells. Three replications of porous-cup samplers were installed at four depths below the soil surface, 25 cm (10 inches), 60 cm (2 ft), 140 cm (4.5

Figure 11. Instrumentation at Arena Research Site



ft), and 250 cm (8 ft). Note that no 250-cm-deep porous-cup samplers were installed in any of the NT, polymer or No-N plots. Water sampling for tillage comparisons was restricted to irrigated, no-polymer plots. Water sampling for polymer comparisons was restricted to irrigated, MB plots. All MB, no-polymer plots were monitored with porous-cup-samplers. Porous-cup samplers were connected to a distributed vacuum system in 1990; however, in 1991 vacuums were placed on each sampler individually to reduce the impact of sampler failure on overall sample collection. Samples of soil water were removed from samplers about once a week, more frequently during periods of greater water input by rainfall and/or irrigation. These soil-water samples were vacuum siphoned into 0.5-L glass bottles, packed in ice and taken to the laboratory. Solution samples were kept at 4°C until analysis.

Soil cores were taken from each tillage subplot to a maximum depth of 2.3 m (7.5 ft) prior to herbicide application and three times after application (Table 7). Cores were obtained with a truck- or tractor-mounted hydraulic probe except in July 1990, where samples were collected with hand probes and augers. Surface samples (0 to approximately 90 cm) were encased in 4.34 cm i.d. (1.71 inches) or 6.86 cm i.d. (2.7 inches) acetate sleeves, all subsurface (90 to 230 cm) cores were encased in 4.34 cm i.d. sleeves. In 1990, all cores were capped, labeled and stored on ice in the field and transferred to the laboratory, where they were stored at -15°C until sectioning and extraction. The 1990 depth increments were nominally 0 to 5, 5 to 20, 20 to 50, 50 to 85, 85 to 110, 110 to 170, and 170 to 230 cm. All 1991 soil cores were taken in three steps: 0 to 90 cm (6.86 cm i.d.), 90 to 170 cm (4.34 cm i.d.), and 170 to 230 cm (4.34 cm i.d.). To reduce overall sample preparation and storage space, cores were sectioned, mixed, subsampled, labeled, and stored on ice in the field. Depth increments for 1991 soil samples were: 0 to 5, 5 to 20, 20 to 50, 50 to 90, 90 to 130, 130 to 170, 170 to 230 cm (seven increments).

Four groundwater monitoring wells were installed at the site (Fig. 3) in October 1989 by the Wisconsin Geological and Natural History Survey. Three shallow [approx. 15 ft (4.6 m)] wells were installed with 5 ft (1.5 m) screens at the water table. The other well was installed to a depth of 25 ft (7.6 m).

In April 1991, 28 piezometer-type wells in 14 nests were installed immediately down gradient from each irrigation block and MSEA plot (Fig. 3). In each nest, one piezometer is screened at the upper 3 ft (0.91 m) of the aquifer, based on the spring water table height. The second piezometer in each nest is screened at 5 to 6 ft (1.5 to 1.8 m) below the spring water table (Fig. 11). Piezometers were constructed of 0.5 inch (1.27 cm) o.d. high density polyethylene (HDPE) semi-rigid tubing perforated at the bottom and screened with stainless-steel wire cloth (mesh = 150 x 150). Piezometers were installed in a manner similar to that described by Stites and Chambers (1991). A length of 0.25 inch o.d. (0.64 cm) HDPE semi-rigid tubing was placed at the bottom of each shallow piezometer to facilitate sample extraction when the water table dropped below the top of the screen. Samples were collected by applying a vacuum on a sample bottle that was connected to the piezometer and pulling the sample to the surface.

Table 7. Soil sampling Arena research site, 1990 and 1991.

Date	DY	DAA*	Total water input since application Depth	ET+**	ET	No-I
		cm	inches			
			1990			
23 April	113	--	180			
4 June	155	24	145	2.88	2.88	2.88
24 July	205	74	230	14.14	13.34	11.52
1 Nov.	305	174	230	28.88	25.98	21.22
			1991			
25 April	115	--	230			
12 June	163	35	230	3.51	2.80	2.13
29 July	210	82	230	15.10	13.52	7.79
16 Oct.	289	161	230	28.19	25.25	16.17

* DAA = days after application.

** ET+ = irrigated at 1.5 inches of rainfall plus irrigation per week; ET = irrigated to meet evapotranspiration according to WISP; No-I = no irrigation.

Herbicide and Nitrate Analysis

Concentrations of five solutes (atrazine, alachlor, metolachlor, bromide, and nitrate) were determined in soil and water from the research site. Herbicides concentrations were determined using a Hewlett-Packard 5890A gas chromatograph (GC) in the Nonpoint Source Pollution Project Laboratory in the Department of Soil Science. The GC was equipped with a megabore (10 m by 0.53 mm i.d.) capillary column of intermediate polarity (5/95 phenyl/methyl liquid stationary phase). The characteristics of the mobile-phase were: support, H 3.5 mL/min-Air 100 mL/min; carrier, He 10 mL/min; and makeup, He 20 mL/min. The analytes were measured with a nitrogen-phosphorus detector. Soil-solution subsamples analyzed for herbicides were placed into C-18 solid-phase extraction (SPE) tubes, extracted and concentrated with methanol before GC analysis. Herbicides were extracted from soils with 4:1 v/v methanol: water solutions, concentrated, and then isolated by SPE prior to GC analysis.

Quality assurance and quality control procedures included about 5% duplicates and matrix blanks. In addition, one laboratory-fortified spike was analyzed every 11 samples.

Prior to July 1991, all groundwater samples from standard monitoring wells were analyzed by the Univ. of Wisconsin-Madison, State Laboratory of Hygiene. Piezometer samples and subsequent monitoring well samples were analyzed in the Department of Soil Science.

Nitrate and bromide concentrations in soil-solution and piezometer sub-samples were determined on a Dionex ion chromatograph at the UWEX Soil and Forage Analysis Laboratory, Marshfield, WI. Inorganic ions were extracted from 1990 soil samples with distilled water and determined by automated analysis and ion selective electrode in the Department of Soil Science. Nitrate concentrations in 1991 soil samples were determined at the UWEX Soil and Plant Analysis Laboratory, Madison, WI.

Yield Determination

Two, 30 ft (9.1 m) long yield rows in each sub-sub-plot were hand harvested and shelled 5 October 1990 (DY 278) and 7 October 1991 (DY 280) for corn grain yield, moisture content, and percent N (1991 only) determination. Total dry matter accumulation was measured on 9 July 1991 (DY 190) and 25 September 1991 (DY 268). Total N uptake was determined on the 25 September sampling.

RESULTS AND DISCUSSION

Rainfall, Irrigation, Water Balance

1990 Growing Season

About 1 inch above-normal rainfall was received in the month of May, and by late August the region had received over 3 inches of rainfall more than the normal (30-year average) growing season. Table 8 shows rainfall and irrigation totals from planting to the end of September at the field site. Figure 12 shows the rainfall and irrigation distribution for the No-I, ET and ET+ blocks graphed with respect to days after herbicide application. Several large rainfall events [≥1 inch (2.54 cm)] occurred throughout the growing season, with the largest event [2.67 inches (6.78 cm)] on the evening of the day nitrogen fertilizer was applied (28 June, DY 179). There were nine events where within 2 days there was greater than 1 inch of total water input by rainfall alone or in combination with irrigation. Measurements of percolation rate show that rainfalls greater than 1 inch (2.54 cm) can result in drainage below the rootzone within 1 day (Fig. 8).

1991 Growing Season

Rainfall during the 1991 season was generally less than normal. By late August, growing season rainfall was about 3.7 inches (9.4 cm) below normal and 6.3 inches (16 cm) less than the same period in 1990. However, total water inputs for irrigated blocks were only about 1.3 inches (3.3 cm) less for 1991 compared to 1990. Considerably more irrigation was required during the 1991 season (Table 8). Similar to 1990, there were several large rain events with several occurring near the time of nitrogen application (Fig. 13). There were six, 2-day periods where greater than 1.6 inches (4.1 cm) of total rainfall/irrigation was received. The risk of receiving a substantial rainfall within a day of irrigation is high and can result in "hydrologic overload" for this soil and rapid percolation to the groundwater.

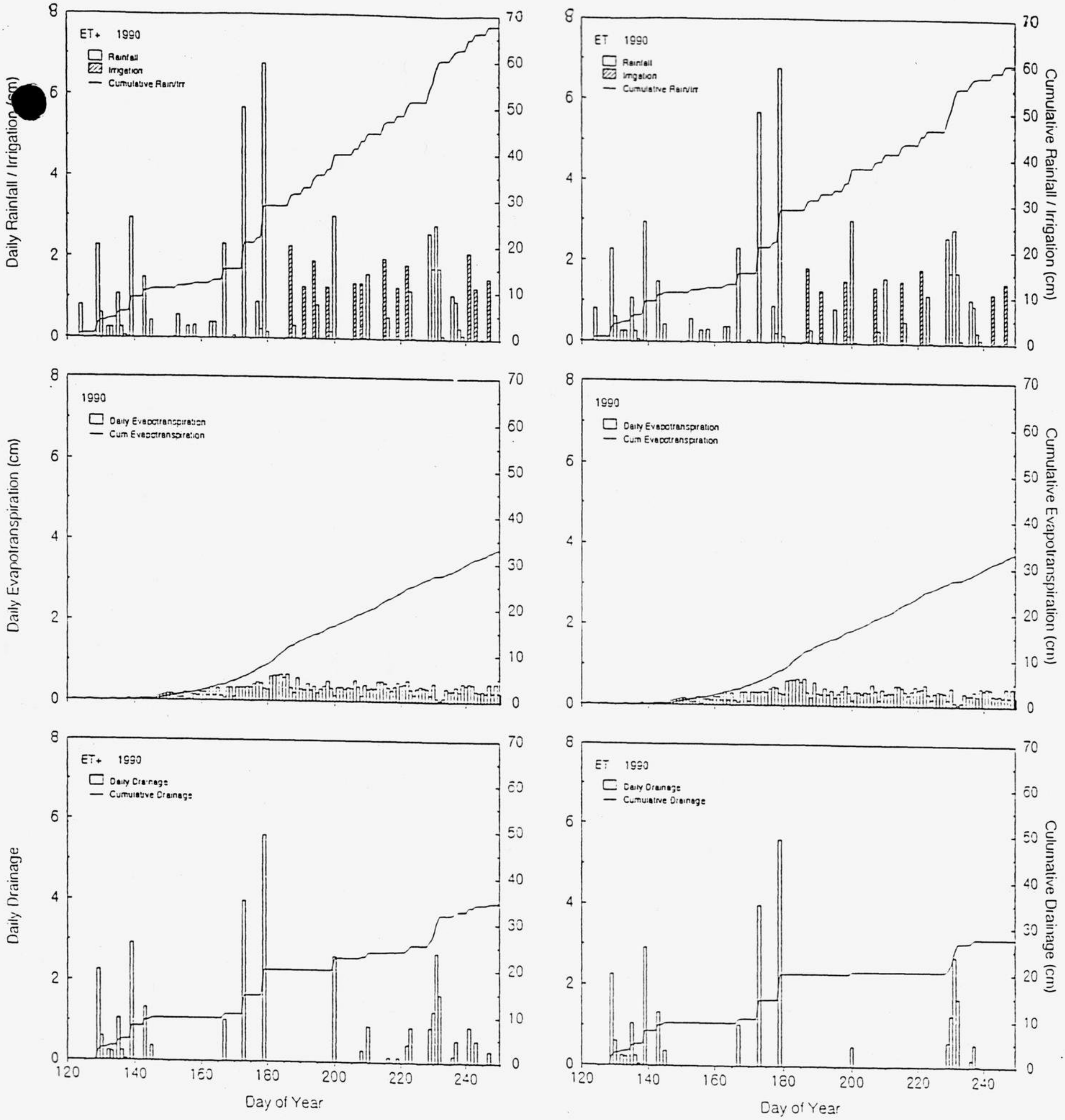


Figure 12. Daily and cumulative, rainfall and irrigation, evapotranspiration, and drainage for ET and ET+ irrigation treatments, LWRV-Arena, 1990. Herbicides applied on day of year 131 (11 May).

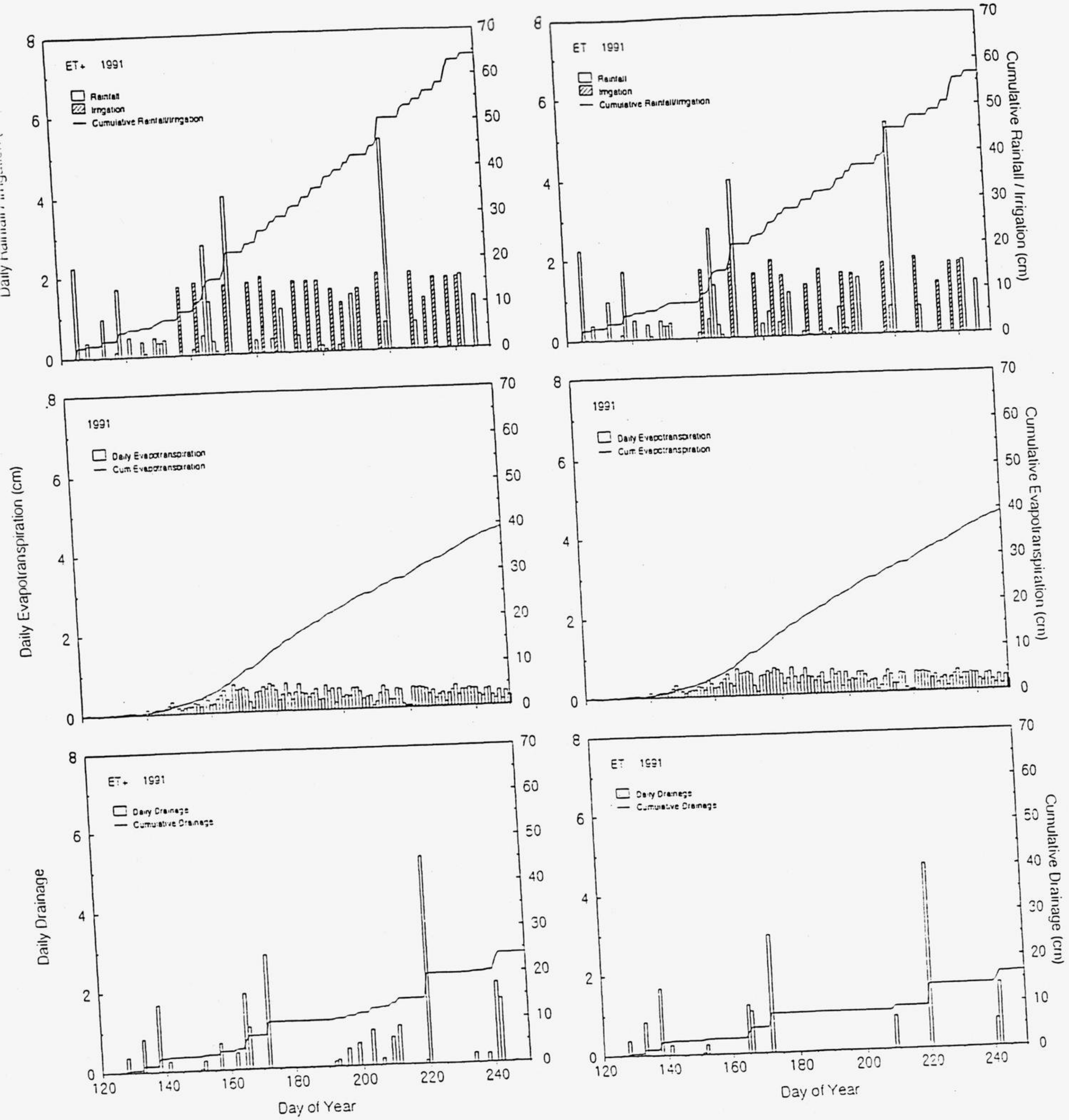


Figure 13. Daily and cumulative, rainfall and irrigation, evapotranspiration, and drainage for ET and ET+ irrigation treatments, LWRV-Arena, 1991. Herbicides applied on day of year 128 (8 May).

Table 8. Precipitation and irrigation at the Arena field site, 1990 and 1991, 29 April (day of year, DY 119) to 29 September (DY 272).

Treatment	Irrigation*		Total		30-yr average
	1990	1991	1990	1991	
	inches (cm)				
No-I**	0.0	0.0	19.9(50.5)	16.0(40.6)	19.8(50.3)
ET	4.8(12.2)	9.1(23.1)	24.7(62.7)	25.1(63.8)	
ET+	7.6(19.3)	12.0(30.5)	27.5(69.9)	28.0(71.1)	

* 1990: First irrigation 6 July (DY 187); last irrigation 4 September (DY 248);
1991: First irrigation 29 June (DY 180); last irrigation 29 August (DY 241).

** No-I = no irrigation; ET = irrigated to meet evapotranspiration according to WISP; ET+ = irrigated at 1.5 inches of rainfall plus irrigation per week.

Field Water Balance and Drainage

Water drainage from the rootzone (100-cm depth) was calculated for each irrigation block. Daily rainfall and irrigation are shown in Figure 12 (1990) and Figure 13 (1991). Daily evapotranspiration (Fig. 12 and 13) was calculated by a modified Priestly-Taylor equation (Priestly and Taylor, 1972) based on temperature and solar-radiation values measured continuously at the field site by the automated weather station and canopy cover. Daily rootzone water depletion status was determined by subtracting daily evapotranspiration from field water capacity (profile water content after free drainage of a fully wetted profile). Daily rainfall and/or irrigation in excess of the rootzone water depletion status resulted in drainage.

Daily drainage for 1990 and 1991 are shown at the bottom of Figures 12 and 13, respectively. Drainage is primarily driven by large rainfall events and the often unavoidable situation where a moderate rainfall follows an irrigation. Cumulative growing season drainage was 46 to 50% of total rain plus irrigation in 1990 and 29 to 37% during 1991. There were fewer large rainstorms and greater evapotranspiration in 1991, giving rise to less overall drainage than the 1990 season. Based on this technique, there was about 2.8 inches (7 cm) additional drainage from ET+ treatments compared to ET treatments. No differentiation was made for evapotranspiration calculations between the two irrigation treatments.

Drainage in the non-irrigated treatments has not been calculated at this time because the occasionally stressed condition of the No-I corn plants violate assumptions of the Priestly-Taylor evapotranspiration techniques.

Soil-Water Atrazine Concentration

Over the course of the 1990 growing season, about 650 soil-water samples were collected and analyzed for herbicide and nitrate. These samples were collected on 20 separate sampling days. On any particular sampling day, several samplers may not have collected samples because of dry conditions, particularly in No-I plots, or because of equipment failure.

Porous-cup soil-water samples were collected on 16 sample dates in 1991. Herbicide concentrations were determined on about 750 samples and nitrate concentrations on 1080 samples.

1990

Herbicide transport assessment during the 1990 field season focused mainly on comparisons among irrigation treatments within the MB tillage no-polymer treatment (conventional or standard treatment). Average atrazine concentrations in soil-solution at three depths with respect to time for the three levels of water input are shown in Figure 14. In general, atrazine concentrations in porous-cup solution samples were less than 20 µg L^{-1} (ppb) for the entire growing season for all three water management regimes. Early increases in atrazine soil-solution concentration are associated with several significant rainfall events within the first 15 days after herbicide application (11 May, DY 131). Atrazine concentrations greater than 10 ppb were measured at 140 cm (4.5 ft) within 40 days after application (DAA).

Between DY 162 and 179 (last 2 weeks of June), 16.0 cm (6.28 inches) of rainfall were received at the site, creating a pulse in the atrazine concentration from DY 181 to 201. Combining average concentrations at the 140-cm depth during this period with the approximately 10 cm of drainage (Fig. 12) gives a loading of 1 to 2% of that applied (about 0.01 lbs/a). This rapid response to large rainfall events demonstrates that this soil is very susceptible to atrazine leaching loss. Given the small sorption capacity and rapid percolation rates of this soil coupled with the shallow depth to groundwater (about 3 m), atrazine that was measured in the lower soil profile likely reached the groundwater during the growing season.

There were no dramatic differences in soil-solution atrazine concentrations among the irrigation treatments (Fig. 14). Most of the major leaching events occurred prior to the first irrigation (DY 187, 56 DAA); therefore, it was difficult to evaluate the influence of irrigation on herbicide transport. Even in the No-I treatment, significant concentrations were measured deep in the profile, re-emphasizing that atrazine leaching at the site is primarily a rain-driven process; however, peak concentrations were generally less than irrigated treatments.

Mean atrazine concentrations were similar in no-tillage (NT) and moldboard plow (MB) tillage treatments (Appendix A, Fig. 1 and 2). Large differences were not expected in the short-term tillage treatments (1990 second year). Trends in atrazine concentrations associated with the tank mix polymer (Acrysol ASE 108) treatments were similar to the non-polymer treatments. Peak atrazine concentrations were measured between 50 and 70 DAA immediately following the large rainstorms.

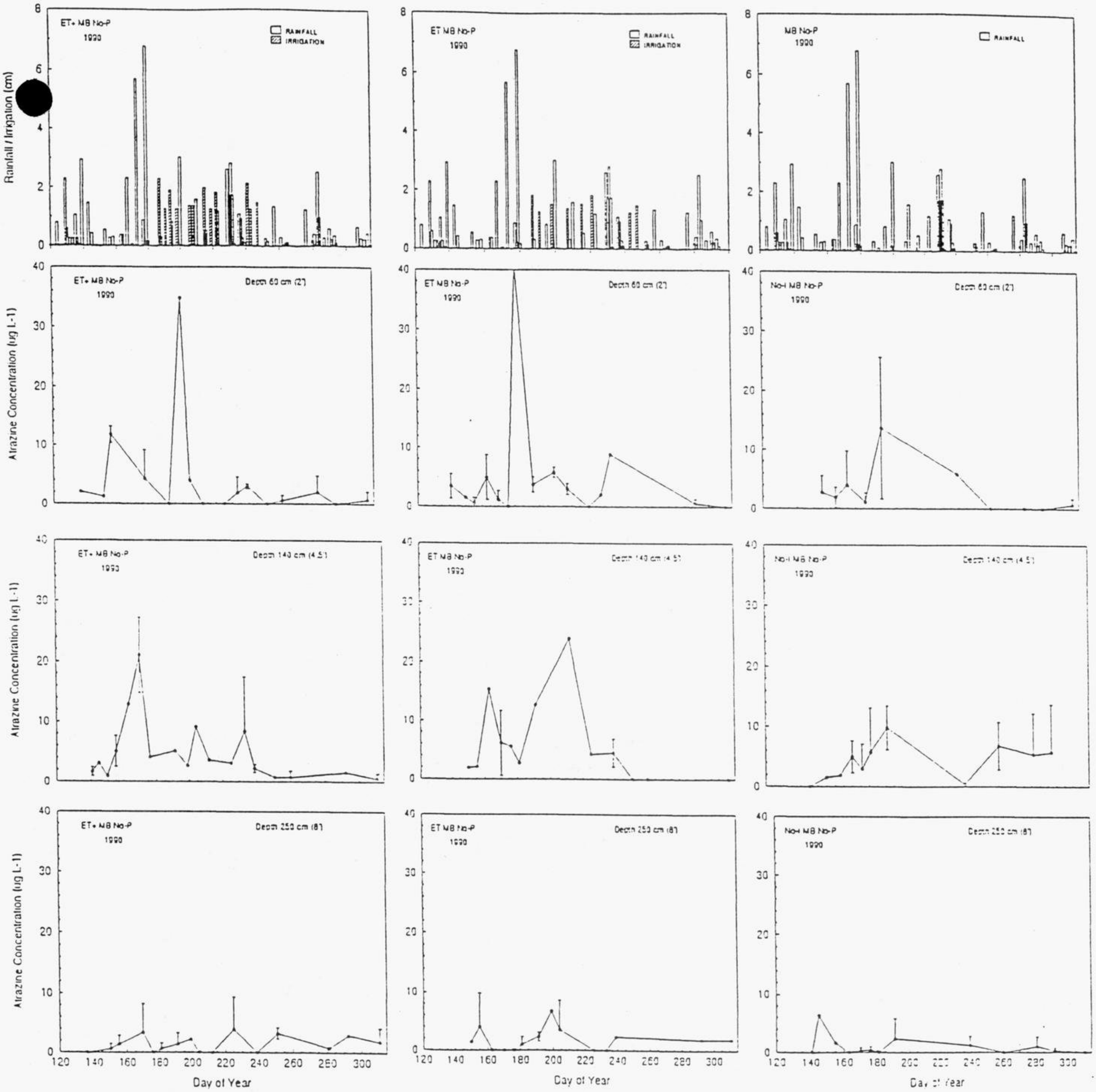


Figure 14. Rainfall and irrigation distribution, and average soil-water atrazine concentration for moldboard plow tillage (MB), no-polymer (No-P) irrigation comparisons, 1990. No-I is no-irrigation, ET is irrigation to meet evapotranspiration, and ET+ is irrigation to exceed ET. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. Herbicides applied day of year 131 (11 May).

Over the course of the 1990 growing season, about 650 soil-water samples were collected and analyzed for herbicide and nitrate. These samples were collected on 20 separate sampling days. On any particular sampling day, several samplers may not have collected samples because of dry conditions, particularly in No-I plots, or because of equipment failure.

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There were no dramatic differences in soil-solution atrazine concentrations among the irrigation treatments (Fig. 14). Most of the major leaching events occurred prior to the first irrigation (DY 187, 56 DAA); therefore, it was difficult to evaluate the influence of irrigation on herbicide transport. Even in the No-I treatment, significant concentrations were measured deep in the profile, re-emphasizing that atrazine leaching at the site is primarily a rain-driven process; however, peak concentrations were generally less than irrigated treatments.

Mean atrazine concentrations were similar in no-tillage (NT) and moldboard plow (MB) tillage treatments (Appendix A, Fig. 1 and 2). Large differences were not expected in the short-term tillage treatments (1990 second year). Trends in atrazine concentrations associated with the tank mix polymer (Acrysol ASE 108) treatments were similar to the non-polymer treatments.

1991

There were low-level detects of atrazine in 140- and 250-cm porous-cup solution samplers that remained in the soil prior to herbicide application in 1991. It is likely that several of the 250-cm samplers, particularly those in the ET+ block, collected groundwater early in the growing season because of a high water table. Comparisons between average atrazine concentrations in soil-water between the different water regimes are shown in Figure 15. Average peak concentrations were less in 1991 than in 1990. However, there was evidence of rapid movement of atrazine deep into the rootzone and vadose zone.

Generally, peak concentrations of atrazine were measured between 30 and 60 DAA and corresponded closely to major rain events during mid-June. Peak concentrations at the 250-cm (8.2-ft) depth were less than 4 µg/L. Concentrations up to 3 µg/L were measured at 250 cm under the No-I treatment. Differences in average atrazine concentrations between the three water management regimes were small, with overall seasonal mean concentrations at 140 cm ranging from 0.6 to 2.3 ppb (coefficient of variation about 110%). However, it is likely there was less overall drainage under the No-I treatment, resulting in less loading to groundwater relative to the irrigated treatments. Further statistical data analysis of water and atrazine flux is needed.

Again, tillage and the polymer (Acrysol ASE 108) effects on atrazine concentrations in soil-water samples were small. Comparisons of mean atrazine concentrations for each irrigation, tillage, and polymer combination are presented in Appendix A (Fig. A2 to A5).

Groundwater Monitoring Results

The four groundwater monitoring wells (Fig. 10) were sampled four times in 1990 and five times through October 1991. Groundwater monitoring results are presented in Table 9. Atrazine was detected in MW-1 and the irrigation well. Both wells access water 10 feet or more below the water table. Water table monitoring wells have only contained one very small detection of atrazine. The atrazine deeper in the aquifer is apparently of historical nature (i.e., not from our application). As indicated in Figure 1, groundwater beneath the site flows approximately in the direction from south-southeast to north-northwest. Monitoring well 3 is located in a position to intercept water moving west of the plots, but has not contained detectable levels of atrazine.

Atrazine concentrations from six sampling times from piezometer wells are presented in Table 10. Widespread detections were found in 7 May 1991 sampling prior to herbicide application. Presumably these atrazine detects are from the 1990 herbicide application. The range of concentrations is from <0.3 to 6.5 µg/L; the mean concentration is about 1.1 µg/L. In general, larger concentrations have been detected down gradient from irrigated plots compared to the non-irrigated block. Atrazine concentrations measured in the groundwater are reasonable, given the levels of atrazine measured in soil-solution samples collected from the lower soil profile.

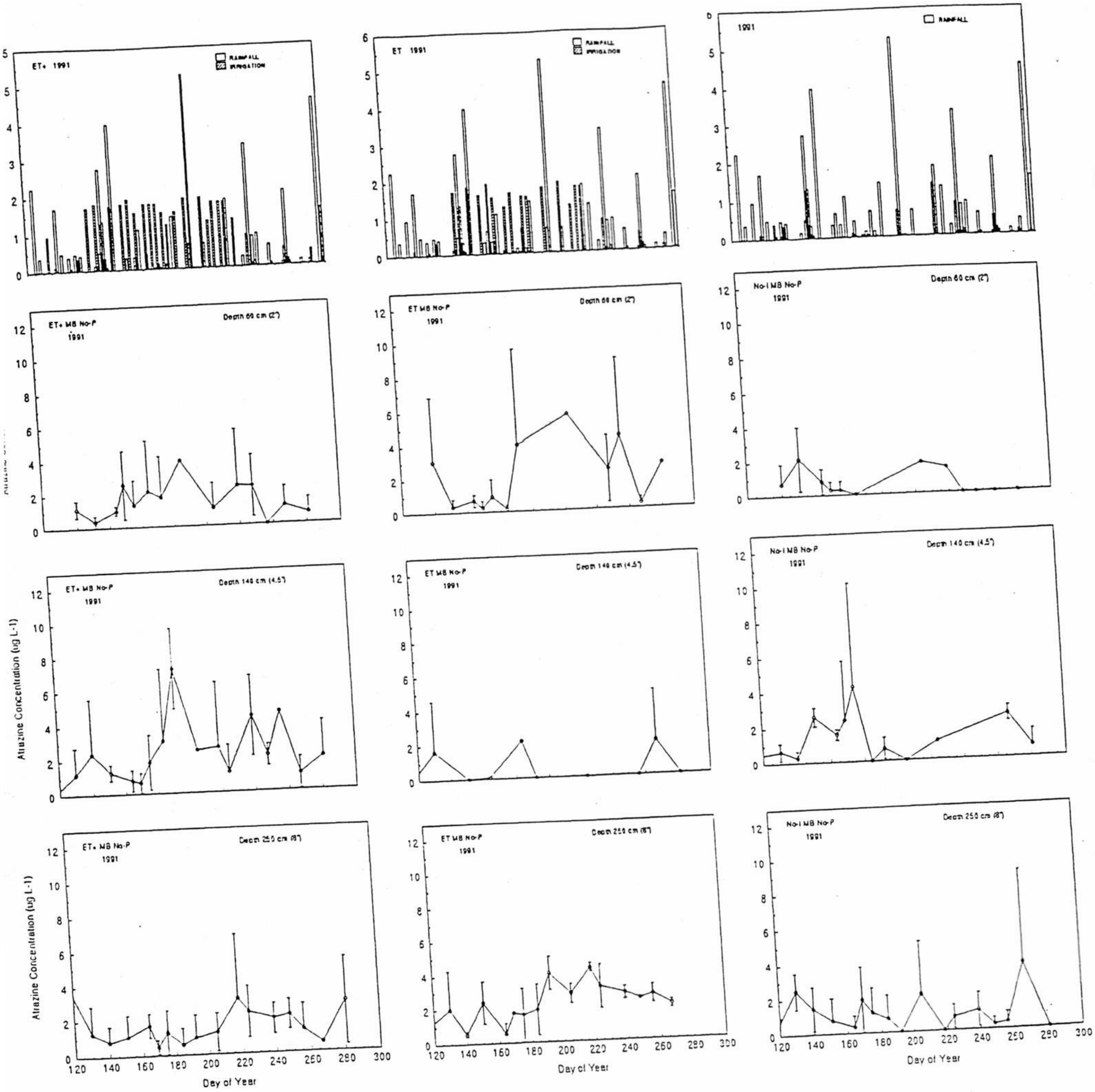

Figure 15. Rainfall and irrigation distribution, and average soil-water atrazine concentration for moldboard plow tillage (MB), no-polymer (No-P) irrigation comparisons, 1991. No-I is no-irrigation, ET is irrigation to meet evapotranspiration, and ET+ is irrigation to exceed ET. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. 'Herbicides applied day of year 128 (8 May).

Table 9. Groundwater monitoring results, LWRV-Arena Project, 1990/91, Dept. of Soil Science, Univ. of Wisconsin-Madison.

Sample date	Day of year	MW-1* (AO211)	MW-2 (AO212)	MW-3 (AO213)	MW-4 (AO214)	IRR-1 (11354)
		Atrazine concentration** (µg/L)				
20 March 90	79	4.3	ND***	ND	ND	--****
31 May 90	151	2.1	ND	ND	ND	--
12 Sept. 90	255	1.5	ND	ND	ND	0.26
14 Nov. 90	318	3.7	ND	ND	ND	0.23
26 March 91	85	2.4	ND	ND	ND	0.17
5 June 91	156	2.0	ND	ND	0.12	0.15
15 Aug. 91	227	1.5	ND	ND	ND	0.56
10 Sept. 91	253	2.4	ND	ND	ND	1.12
15 Oct. 91	288	1.7	ND	ND	ND	ND
		Deethylatrazine concentration (µg/L)				
26 March 91	85	2.1	ND	ND	ND	0.55
5 June 91	156	1.6	ND	ND	0.31	0.61
		Deisopropylatrazine concentration (µg/L)				
26 March 91	85	2.0	ND	ND	ND	ND
5 June 91	156	1.8	ND	ND	ND	ND
		Nitrate-N concentration (mg/L)				
20 March 90	79	--	--	--	--	--
31 May 90	151	14.8	2.9	5.0	1.5	--
12 Sept. 90	255	13.0	18.2	6.6	0.4	8.4
14 Nov. 90	318	15.2	17.6	6.1	0.8	8.8
26 March 91	85	17.5	21.8	6.47	0.82	8.83
5 June 91	156	19.0	21.7	4.01	3.56	9.07
15 Aug. 91	227	14.9	23.8	15.5	0.5	8.2
10 Sept. 91	253	17.6	17.2	15.3	0.6	9.2

* MW-1 is screened at about 10 ft below the water table; IRR-1 is screened at about 30 to 50 ft below the water table. All other wells are screened at the water table.

** Prior to 5 June 91, all samples were analyzed at the State Lab. of Hygiene. Subsequent samples analyzed in the Dept. of Soil Science. No detections of metolachlor, alachlor, or cyanazine were found for all wells and sample dates.

*** No detection.

**** --, no sample collected.

Table 10. Atrazine concentration in piezometer samples at Arena field site, 1991.

need data

	Piezometer number	5/7/91 DY 127	5/23/91 DY 143	6/28/91 DY 179	8/13/91 DY 225	9/10/91 DY 253	10/10/91 DY 283
		µg/L					
	1	ND*	ND	0.5	ND	ND	ND
	2	ND	ND	ND		**	
ET+	3	2.6	1.7	1.0	1.3	1.7	1.1
	4	1.3	2.0	1.6	1.3	1.5	1.2
	5	1.6	1.7	1.8	1.6	1.9	1.3
	6	1.6	1.6	1.9	1.7	1.4	1.3
MSEA	7	ND	ND	ND	ND	1.1	ND
	8	0.6	<0.3	0.7	ND	2.0	ND
	9	0.4	ND	ND	0.7	1.2	0.9
	10	ND	<0.3	0.5	0.7	0.9	ND
ET	11	1.0	0.6	1.9			
	12	1.7	0.8	1.2	1.8	1.6	1.1
	13	6.5	3.9	2.8	2.8	2.8	5.6
	14	ND	<0.3	0.8	1.2	1.9	1.3
MSEA	15	ND	ND	ND	1.2		
	16	0.6	0.3	1.2	2.9	1.9	1.5
	17	1.0	1.1	1.0	1.6	1.9	0.8
	18	3.4	2.2	4.0	5.6	3.1	2.5
No-I	19	0.5	0.3	0.6	ND		
	20	ND	0.3	0.5	0.9	ND	ND
	21	0.4	0.3	0.7	1.0	1.1	0.7
	22	0.5	<0.3	0.5	1.0	1.0	0.5
	23	0.7	0.8	0.7	1.2	1.4	0.6
	24		<0.3	0.7	1.5	1.3	0.8
MSEA	25	ND	ND	ND	ND		
	26	<0.3	<0.3	0.6	1.2	1.3	0.8
	27	ND	ND	0.5	ND	ND	ND
	28	<0.3	0.6	0.9	1.3	1.5	0.7

* ND = no detection,

** Blank space indicates no sample was able to be collected.

Table 11. Nitrate-nitrogen concentration in groundwater at Arena field site, 1991.

Piezometer number	5/7/91 DY 127	5/23/91 DY 143	6/28/91 DY 179	8/13/91 DY 225	9/10/91 DY 253	10/10/91 DY 283
	----------	----------	---------- NO_3-N	(mg/L) ----------	----------	----------
1	0.2	0.6	1.2	1.9	1.8	1.3
2	0.3	0.5	0.2	*		
3	16.7	18.0	9.7	7.7	6.0	7.2
4	16.9	34.5	13.3	11.4	11.8	13.6
5	18.4	2.7	8.7	7.1	6.0	5.7
6	21.4	16.6	12.0	12.1	8.9	7.7
7	16.1	8.4	7.7	5.0	8.5	8.7
8	23.3	7.9	23.8	6.8	8.2	10.1
9	11.9	13.6	9.3	6.1	7.2	10.2
10	9.3	10.0	15.0	14.1	16.6	17.4
11	19.4	37.5	13.0			
12	33.9	36.9	21.0	27.6	23.4	18.2
13	30.1	10.8	20.4	11.3	11.6	11.3
14	14.3	8.2	15.9	25.0	30.9	25.9
15	15.0	14.8	9.8	7.4		
16	18.7	26.2	22.7	22.1	21.4	13.0
17	20.6	15.8	10.7	7.5	6.7	7.7
18	29.0	36.1	31.7	30.6	21.2	14.2
19	27.5	22.9	17.4	16.3		
20	15.5	47.6	20.2	21.2	25.8	29.2
21	31.4	16.4	26.1	25.9	33.1	20.5
22	25.6	24.0	23.0	29.2	29.1	27.1
23	10.4	7.9	8.1	10.7	7.9	**
24	17.5	17.9	20.3	20.7	30.7	**
25	14.8	23.0	11.1	12.1		
26	23.1	20.7	30.8	17.7	21.4	**
27	32.7	13.9	17.4	11.3	10.7	**
28	18.3	22.6	14.1	12.2	15.4	**

* Blank spaces indicate no sample was collected.

** Sample results were not available.

Nitrate-nitrogen concentrations from monitoring well samples, and piezometer well samples are shown in Figures 9 and 11, respectively. Based on results from MW-1, P1, and P2 (up-gradient sampling points), the level of NO_3-N entering the research site is very small (<2 mg/L) (Table 11). The range of NO_3-N concentrations measured beneath the plot areas is 2.7 to 47.6 mg/L. Temporal and spatial trends of the groundwater NO_3 data are not readily discernible.

Limit of detection for atrazine is nominally 0.3 µg/L; however, the presence of atrazine may have been detected at lower levels depending on volume extracted and GC conditions.

Corn Yield

Corn grain yield data for 1990 are presented in Table 12. In general, no-till treatments yielded more than moldboard tillage treatments and polymer treatments yielded more than no-polymer treatments. The tillage differences are probably due to less wind-erosion damage, as observed on no-till plots, compared to moldboard plow plots. Reasons for the polymer treatment differences are not clear or directly identifiable; however, an interaction with nitrogen is suspected, but is not clearly substantiated by nitrate leaching data. Overall yields were small probably because of substantial nitrate leaching losses as a result of the large precipitation amounts in late June.

Table 12. Corn grain yield, Lower Wisconsin River Valley, Arena Project, 1990.

Treatment*	Moldboard plow tillage		No-tillage	
	No-polymer	Polymer**	No-polymer	Polymer
	bu/A			
ET+	a 108a***	a 126a	a 119a	a 157b
ET	a 103b	a 114ab	b 97b	b 122a
No-I	b 59a	b 63a	b 84b	c 73b
No-I No-N	c 24a	c 21a	c 32a	d 27a

* ET+ = irrigated at 1.5 inches of rainfall plus irrigation per week; ET = irrigated to meet evapotranspiration according to WISP. No-I= no-irrigation; No-I, No-N = no irrigation, no-nitrogen.

** Acrysol ASE 108 polymer added to herbicide tank-mix.

*** Within-row means followed by the same letter are not significantly different at the 0.05 level. Within-column means preceded by the same letter are not significantly different at the 0.05 level.

Grain yield in 1991 was considerably greater than 1990 for irrigation treatments (Table 13) and closer to expected yields under irrigated conditions on this soil. Growing conditions (warmer early season temperatures) and increased nitrogen use efficiency with split applied nitrogen are likely responsible for the yearly differences.

Table 13. Effect of irrigation on corn grain yield at Arena research site, 1990 and 1991.

Irrigation treatment	Grain yield (no-polymer)					
	1990			1991		
	MB	NT	Avg.	MB	NT	Avg.
	bu/a					
No-I	59 a	84 a	71 a	29 a	26 a	27 a
ET	103 b	97 a	100 b	150 b	167 b	158 b
ET+	108 b	119 b	114 c	174 c	183 c	177 c
$LSD_{0.05}$	21.9	15.5	13.6	11.9	13.3	9.3

* MB = moldboard plow tillage; NT = no-till tillage.

** Means within a column followed by the same letter are not significantly different at the 95% level.

Again, there was a general trend of greater yields for polymer-NT treatments compared to no-polymer-MB treatments for irrigated conditions (data not shown). Tillage differences were not significantly different, whereas tank-mix polymer treatments resulted in significant increases relative to no-polymer treatments of 4 to 10% for ET+ and ET irrigation levels, respectively.

Comparing between irrigation treatments (no-polymer) for each tillage and year shows significant increases in grain yield with increased water input (Fig. 13). The substantial increase from No-I to irrigated treatments was expected, especially during the drier 1991 season. However, the reduced yield from the ET-WISP treatment relative to the calendar-type irrigation schedule (ET+) of 1.5 inches (3.8 cm) of total water per week was not expected. Assuming there are no other confounding interactions such as fertility level or herbicide injury, the yield differences are apparently a result of small differences between the amount of profile water depletion prior to each irrigation. It appears that an allowable depletion of 0.85 to 1 inch of profile water between irrigations in the WISP for this site is too large. Based on average profile water depletions on the day prior to each irrigation (Table 14), it is suggested that the optimum (with respect to yield) profile water depletion level is between about 0.8 and 0.5 inches (2 to 1.3 cm). This narrow range creates a great challenge in scheduling irrigation for optimum yields given the fact that daily evapotranspiration can reach 0.25 inch (0.64 cm). Improvements with incorporation of quantitative precipitation forecasts into irrigation schedules may help to reduce drainage from sequential irrigation/rainfall events and still maintain yields.

Table 14. Profile water depletion [Wfc - Wi]* on day prior to irrigation.

Year		Profile water depletion ET**	ET+
		------- inches	--------
1990	Mean	0.956	0.584
	SD	0.349	0.408
	Median	0.835	0.410
	n	8	12
1991	Mean	0.816	0.505
	SD	0.158	0.266
	Median	0.825	0.415
	n	14	18

* Wfc = profile water content at field capacity; Wi = profile water content on day i. The smaller [Wfc - Wi] is, the greater the amount of water "available" for plants.

** ET = irrigated to meet evapotranspiration; ET+ = irrigated at 1.5 inches of rainfall plus irrigation per week.

SUMMARY

Based on the three laboratory/greenhouse studies it appears that differences in herbicide leaching between the LWRV and CS areas are due, at least in part, to a combination of intrinsic factors. Because of uniform grain size distribution and lack of significant morphologic discontinuities in LWRV sand, water percolation is very rapid; thus, solute-to-soil contact time is short. The water holding capacity of the LWRV sand is less than that of the CS soil. Generally, atrazine adsorption is slightly less in the LWRV soil. There is also indirect evidence, from the soil column study, that atrazine degradation may be faster in the CS, leading to less overall leaching. The processes of water movement, sorption, and degradation do not act independent of each other. Sorption and degradation in the unsaturated zone are directly linked to the rate of water movement through the rootzone. The relationship between these processes appears to be unique for each of the soil types.

In situ hydrologic characterization of the soil profile at the field site revealed that drainage is very rapid, with field capacity being reached within 24 hours. Field measurements of unsaturated hydraulic conductivity were about one order of magnitude greater in the Sparta sand compared to previous measurements of Plainfield sand. The moisture regime associated with Sparta sand demonstrates little water holding capacity below 30 cm in the profile. Thus, we speculate that once contaminants reach depths greater than 30 cm, little attenuation is likely to occur due solely to the water flow regime and associated rapid transport.

The 1990 growing season was generally wetter than normal and the 1991 growing season was drier than normal. During both years, several large rainstorms occurred resulting in rapid percolation and drainage. Atrazine concentrations greater than 10 ppb were measured at a depth of 140 cm within 40 days after herbicide application in 1990. Between DY 162 and 179 (last 2 weeks of June), 16.0 cm (6.28 inches) of rainfall were received at the site, creating a pulse in the atrazine concentration from DY 181 to 201. Combining average concentrations at the 140-cm depth during this period with the approximately 10 cm of drainage (Fig. 12) gives a loading of 1 to 2% of that applied (about 0.01 lb/a). This rapid response to large rainfall events demonstrates that this soil is very susceptible to atrazine leaching loss.

Average peak concentrations were less in 1991 than in 1990. However, there was evidence of rapid movement of atrazine deep into the rootzone and vadose zone. Generally, peak concentrations of atrazine were measured between 30 and 60 days after application and corresponded closely to major rain events during mid-June. Peak concentrations at the 250 cm (8.2 ft) depth were less than 4 μg/L. Concentrations up to 3 μg/L were measured at 250 cm under the No-I treatment. Differences in average atrazine concentrations between the three water management regimes were small, with overall seasonal mean concentrations at 140 cm ranging from 0.6 to 2.3 ppb. No appreciable differences in atrazine leaching were measured between tillage and polymer treatments for either year.

The range of atrazine concentrations measured in groundwater during 1991 were from <0.3 to 6.5 μg/L. The mean concentration was about 1.1 μg/L. In general, larger concentrations have been detected down gradient from irrigated plots compared to the non-irrigated block. Atrazine concentrations measured in the groundwater are reasonable given the levels of atrazine measured in soil-solution samples collected from the lower soil profile.

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APPENDIX A

Soil-water atrazine concentration tillage comparisons for irrigated treatments, 1990 and 1991 growing season, LWRV-Arena project (Fig. A1 to A4).

Soil-water atrazine concentration polymer comparisons for irrigated treatments, 1991 growing season, LWRV-Arena project. (Fig. A5 and A6).

APPENDIX B

Copy of Report:

Contamination Attenuation Indices for Sandy Soils: Tools for Information Transfer

Kevin McSweeney, Cathy Seybold, Frederick Madison, and Birl Lowery. Department of Soil Science, University of Wisconsin-Madison

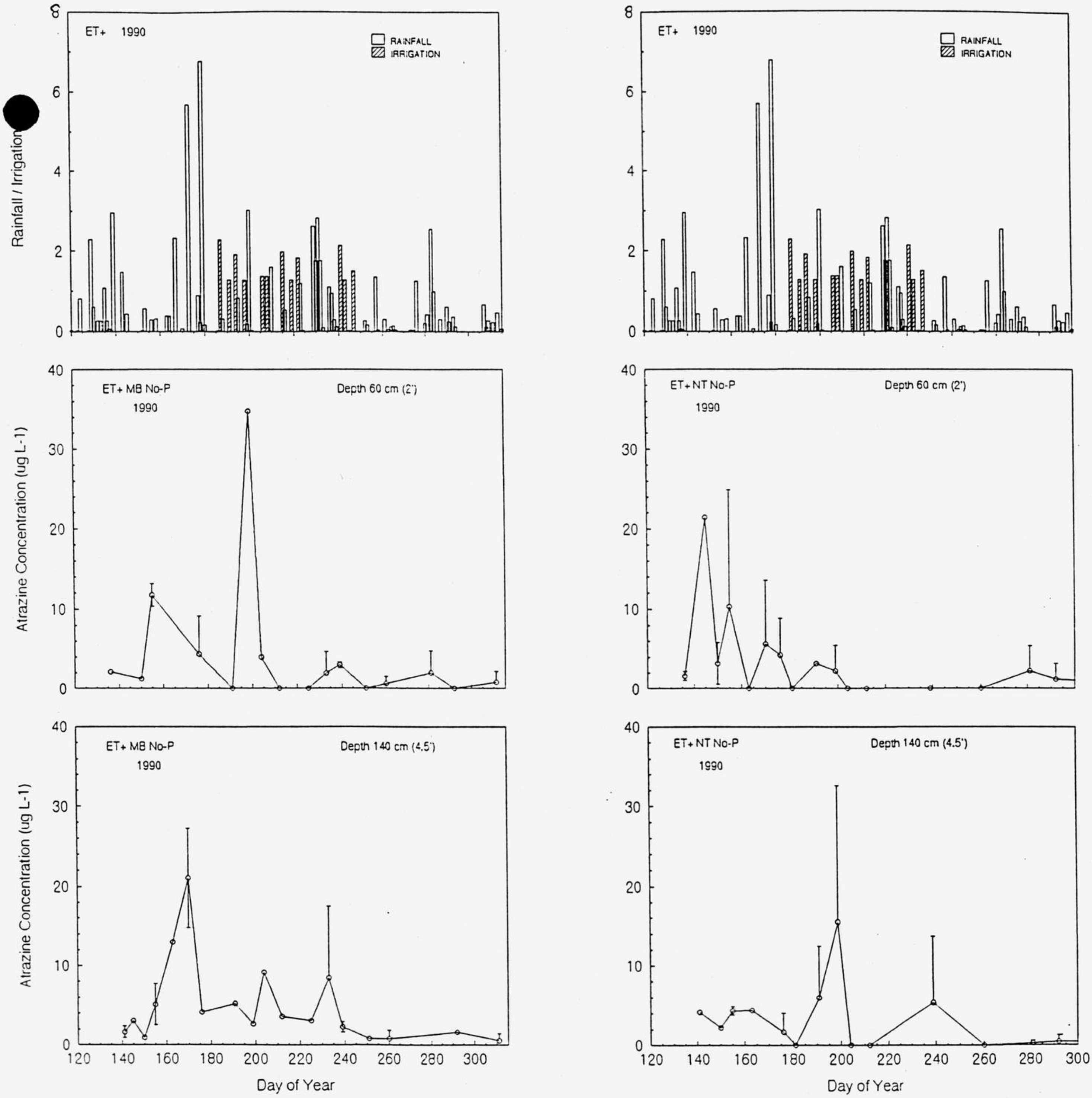

Figure A1. Average soil-water atrazine concentrations for moldboard plow tillage (MB) and no-tillage (NT) comparisons, (no-polymer (No-P), ET+ irrigation treatment) 1990. ET+ is irrigation to exceed evapotranspiration. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. Herbicides applied day of year 131 (11 May).

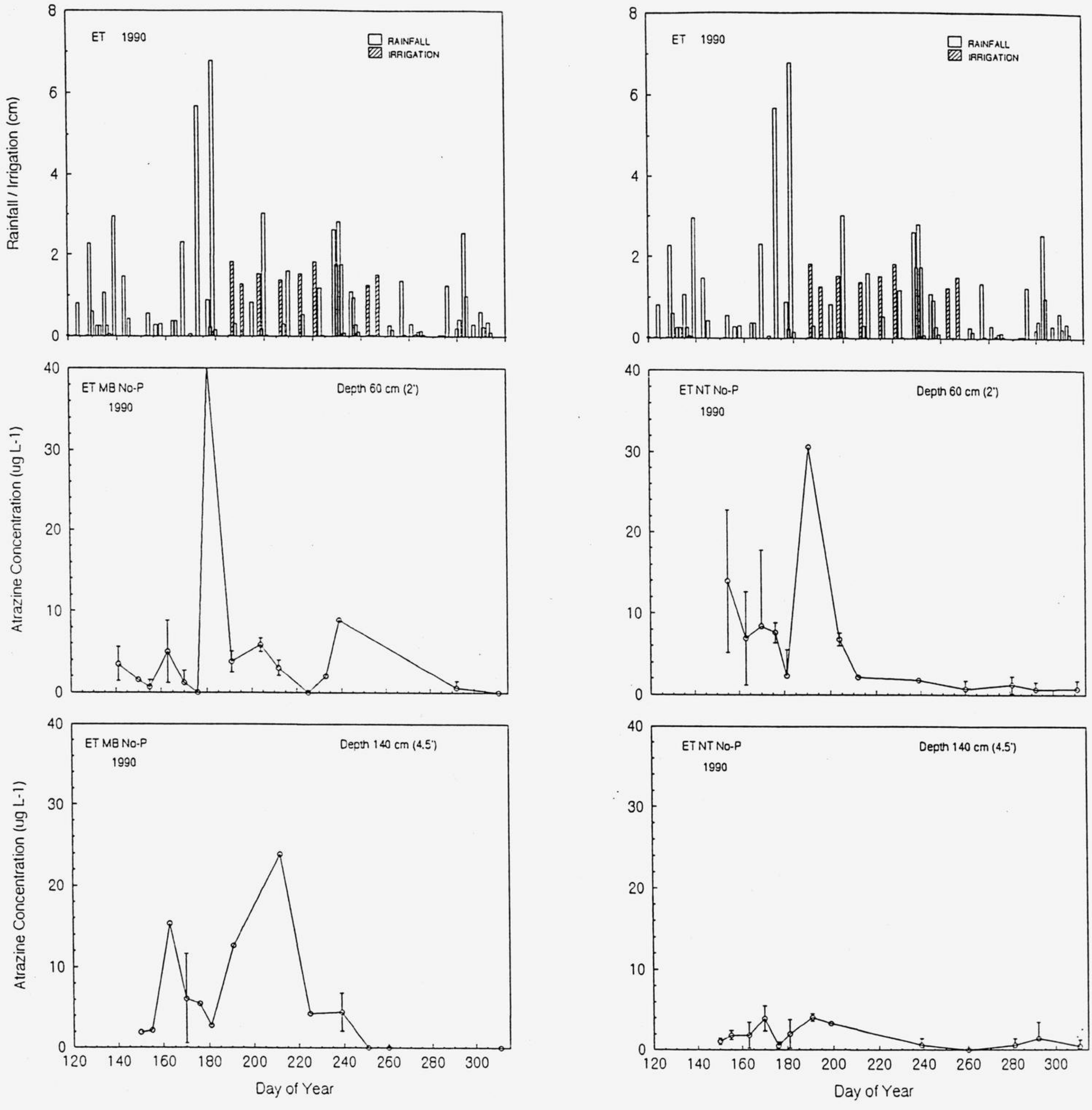

Figure A2. Average soil-water atrazine concentrations for moldboard plow tillage (MB) and no-tillage (NT) comparisons, (no-polymer (No-P) ET irrigation treatment) 1990. ET is irrigation to meet evapotranspiration. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. Herbicides applied day of year 131 (11 May).

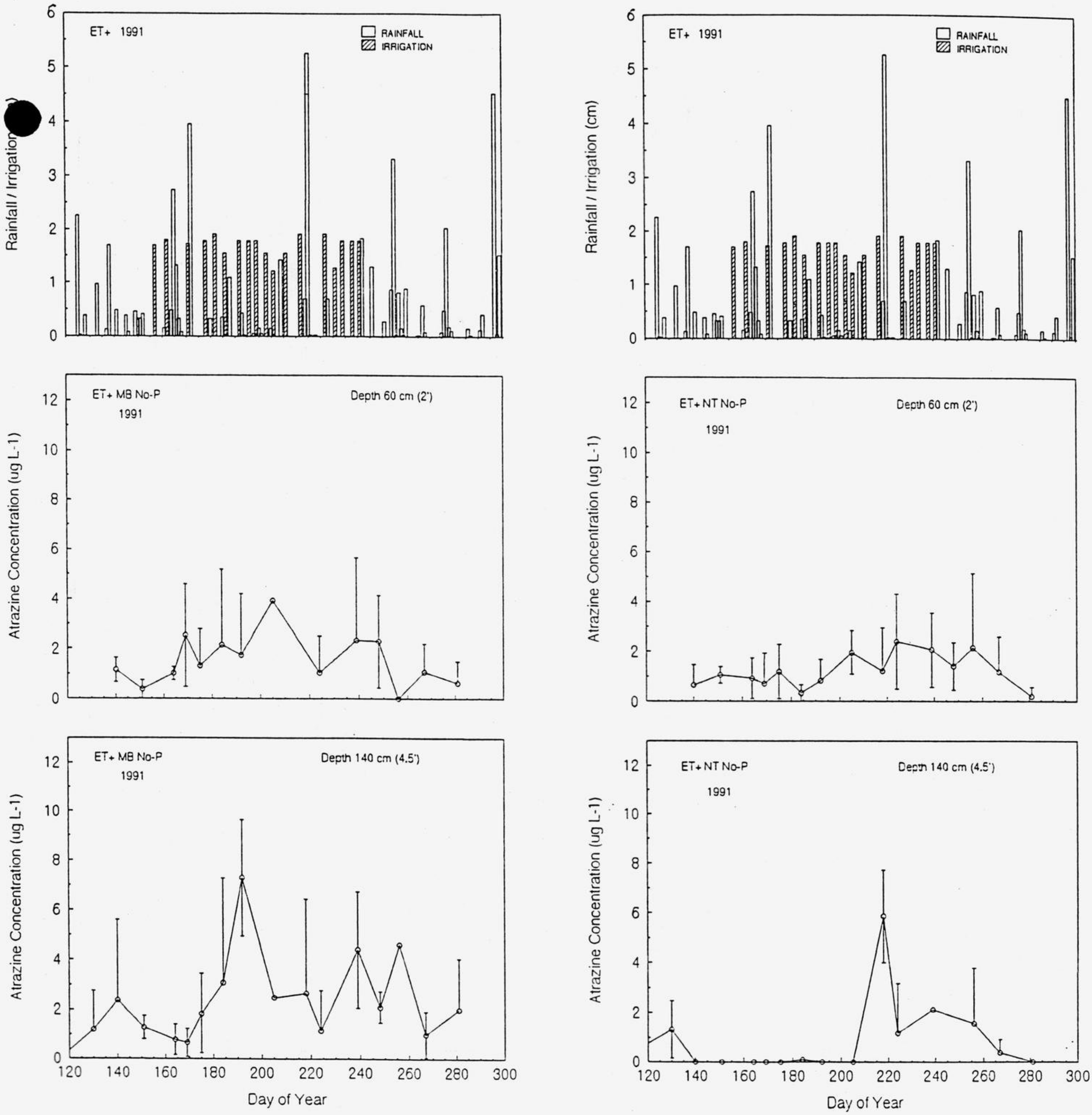

Figure A3. Average soil-water atrazine concentrations for moldboard plow tillage (MB) and no-tillage (NT) comparisons, (no-polymer (No-P), ET+ irrigation treatment) 1991. ET+ is irrigation to exceed evapotranspiration. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. Herbicides applied day of year 128 (8 May).

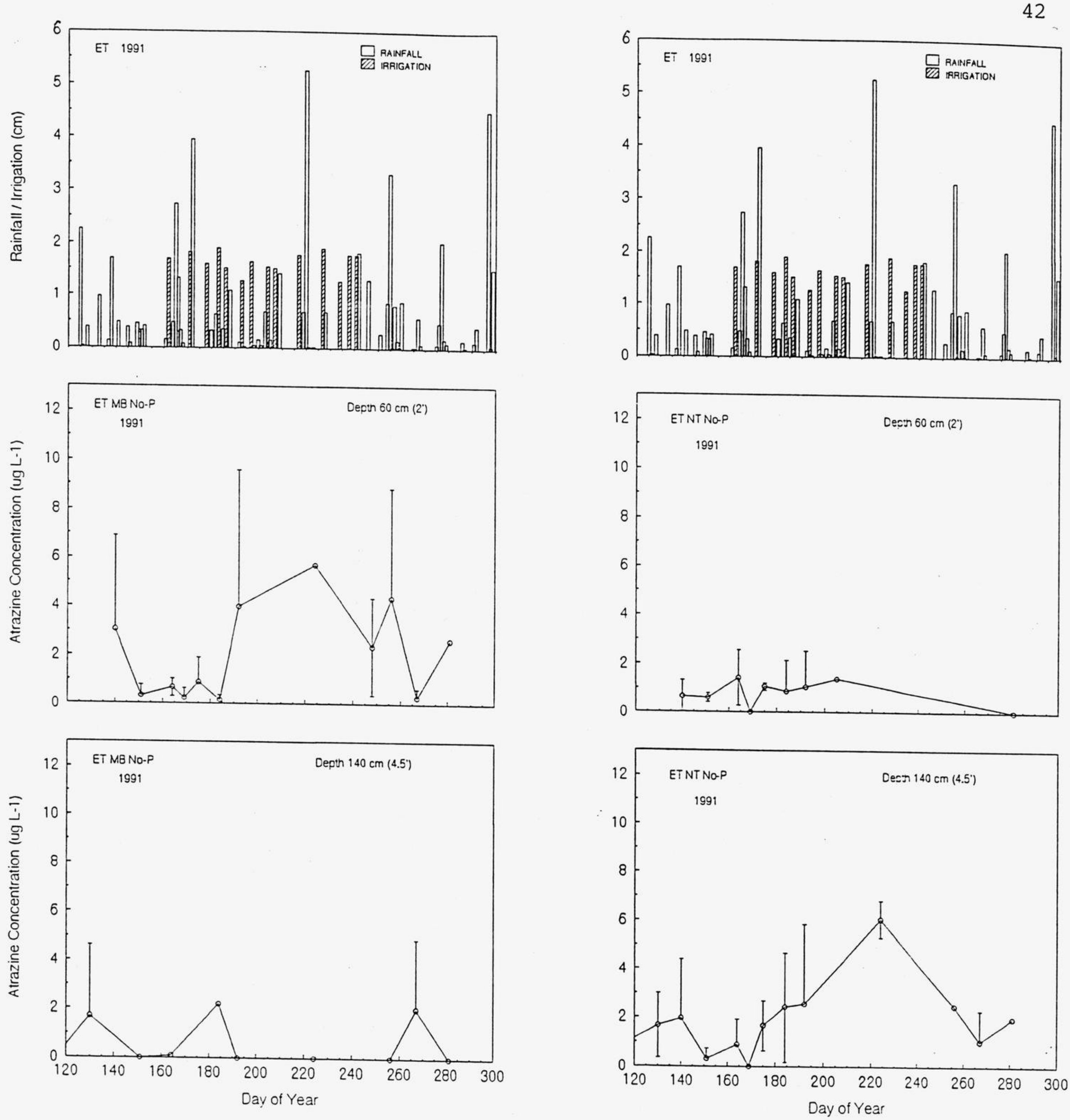

Figure A4. Average soil-water atrazine concentrations for moldboard plow tillage (MB) and no-tillage (NT) comparisons, (no-polymer (No-P) ET irrigation treatment) 1991. ET is irrigation to meet evapotranspiration. Error bars are ± one standard deviation. A point with no standard deviation represents one data point. Herbicides applied day of year 128 (8 May).

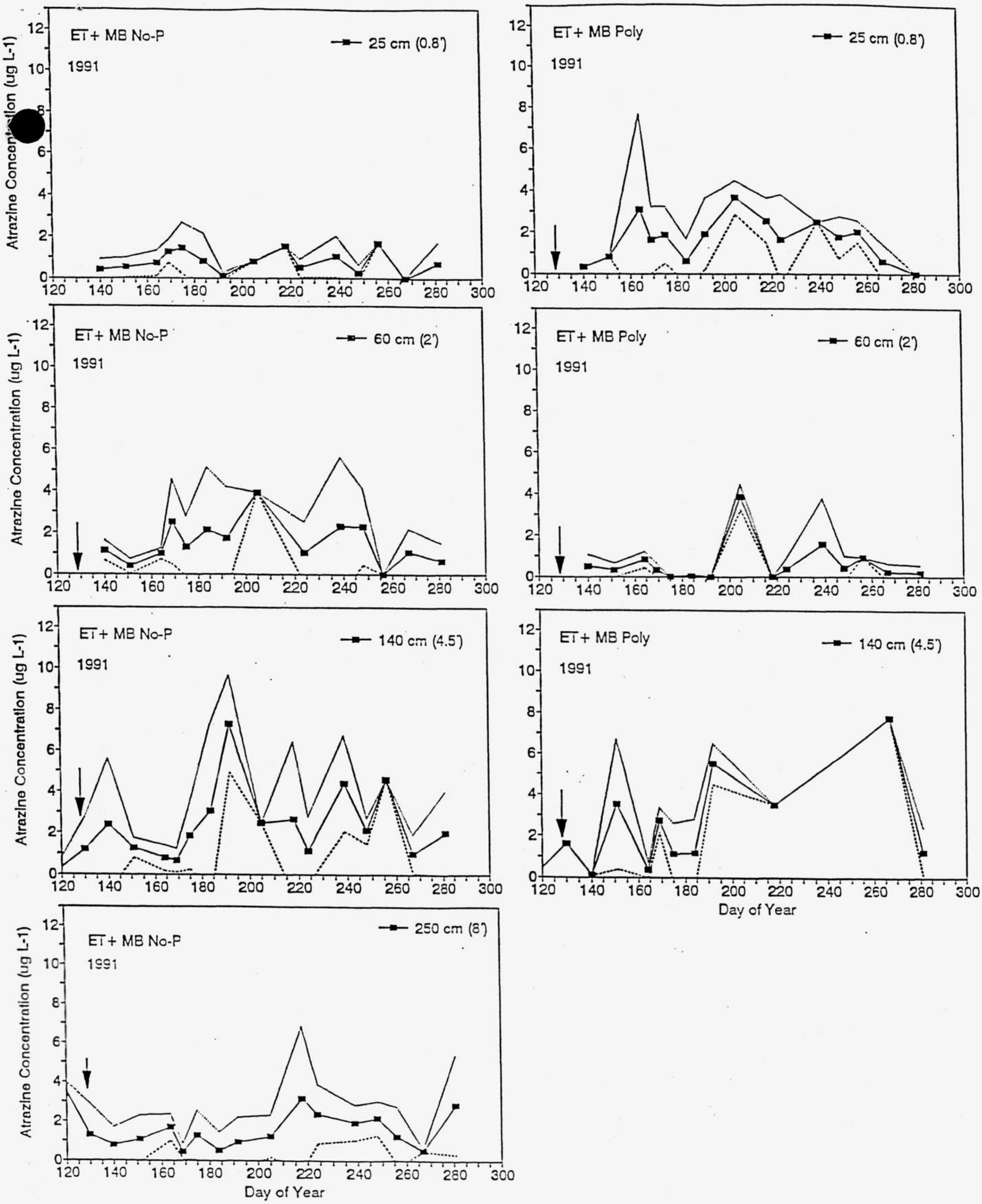

Figure A5. Average soil-water atrazine concentrations for moldboard plow (MB) polymer and no-polymer (No-P) treatments under irrigation to exceed evapotranspiration (ET+). Dotted and dashed lines represent $\pm$ one standard deviation of the mean. A point with no standard deviation represents one data point. Herbicides applied day of year 128 (8 May 1991).

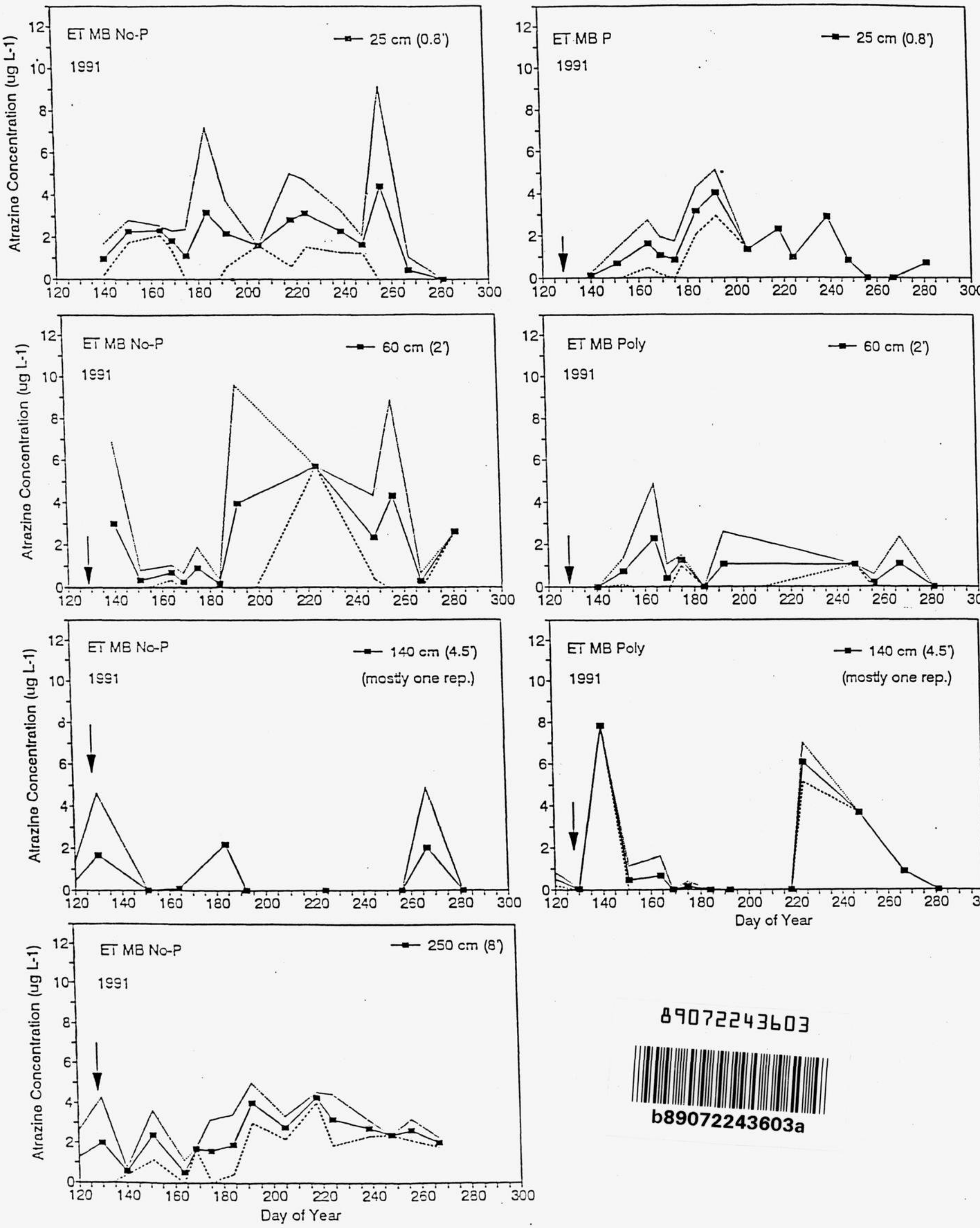

Figure A6. Average soil-water atrazine concentrations for moldboard plow (MB) polymer and no-polymer (No-P) treatments under irrigation to meet evapotranspiration (ET). Dotted and dashed lines represent ± one standard deviation of the mean. A point with no standard deviation represents one data point. Herbicides applied day of year 128 (8 May 1991).