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ABSTRACT

Nitrate (NO_3) contamination of groundwater has been well documented. Nonpoint sources resulting from fertilizer use in agriculture are often to blame for much of this contamination. The research presented in this report was conducted to determine the rate at which nitrogen (N) moves through the root zone to the vadose zone of soils and the groundwater under a sandy soil along the Lower Wisconsin River Valley (LWRV). Rainfall was greater than normal during the 1990 growing season; several large storms caused deep percolation of water and NO_3. The largest storm (7 cm) occurred immediately following N fertilizer application, creating a worst-case scenario with respect to NO_3 leaching. As a result of this storm, appreciable increases in NO_3-N in soil-solution occurred as deep as 250 cm (8 ft) in the 12 days following N application. A six-fold increase in NO_3-N concentrations was found in groundwater samples collected adjacent to the research plots 2 months after nitrogen fertilization.

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INTRODUCTION

Groundwater pollution by agrichemicals is a major concern in the Midwest. Of all the potential groundwater pollutants, nitrate (NO_3) is the most common in Wisconsin and (Wisconsin Department of Agriculture, Trade and Consumer Protection, 1989) the Midwest. About half of the United States and 95% of rural households depend on groundwater for their drinking water (CAST, 1985). The extent of nitrate contamination and the processes that govern agrichemical transport must be known and understood to mitigate nitrate contamination. Development and implementation of cost-effective best-management practices (BMPs) that reduce contaminant loads to surface and groundwater are needed to reduce degradation of water quality.

Agricultural land use directly influences the amount of nitrate in groundwater. Nitrate-N concentrations under potato fields have been reported to be > 10 mg/L, whereas concentrations were < 1 mg/L in groundwater beneath forests or pastures (Hill, 1983). Burkart and Kolpin (1993) found that wells located in areas containing at least 25% corn or soybeans had higher concentrations of nitrate than well sin less densely cropped areas. Groundwater contamination was also more common where fertilizer rates were higher and where crops were irrigated. The influence of tillage on nitrate leaching has been variable, Kitur et al. (1984) found equal NO_3-N losses under no-tillage and conventional tillage systems, while other studies (Kanwar et al., 1988; Drury et al., 1993) have found greater NO_3-N leaching under conventional tillage than no-tillage systems.

Wisconsin has played an important role in raising concern about pesticides and NO_3 in groundwater. The Central Sands Area of Wisconsin has been the focus of numerous studies on NO_3 movement, (Endelman et al., 1974; Saffigna and Keeney, 1977; Jackson, 1987), however, few studies have been made in the Lower Wisconsin River Valley (LWRV). The LWRV consists of intensively cropped, irrigated, sandy soil landscapes that are particularly susceptible to groundwater contamination by agrichemicals. Nitrate has frequently been detected in groundwater monitored down-gradient from irrigated fields in this area (Postle, 1989). Furthermore, many of the detects exceeded the national drinking water standard for NO_3-N (10 mg/L, ppm), with the average concentration being 30 ppm.

This study was initiated to assess the rates of nitrate and water movement to groundwater in the LWRV and to evaluate potential BMPs to reduce groundwater contamination. The effects of irrigation and tillage systems on corn yield and movement of water and NO_3 through the unsaturated zone of a sandy soil in the LWRV were evaluated. Although no previous studies have been performed on nitrate, preliminary studies have indicated that adding polymers during pesticide application decreases pesticide leaching (Alva and Singh, 1991; Jain and Singh, 1991; Wietersen et al., 1993). Therefore, the potential of adding a polymer to reduce nitrate leaching in this soil was also examined.

MATERIALS AND METHODS

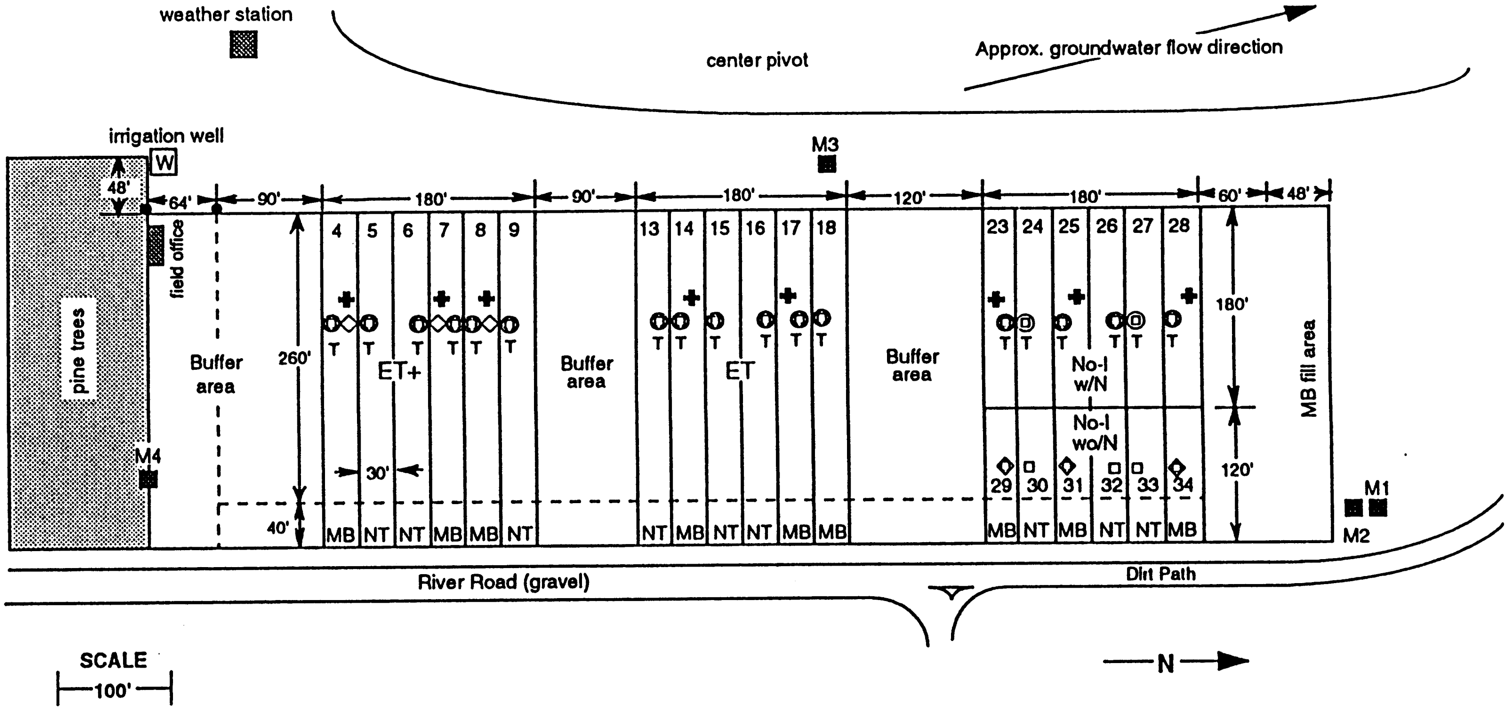
An instrumented field experimental site was established on a 2.8-ha (7-acre) field located north of Arena in Iowa County, Wisconsin. A schematic field plan of the research site, showing the location of scientific instruments and experimental treatments, is illustrated in Figure 1. The field experimental design has a split-split unbalanced block design. The main-block treatments were irrigation and fertilization. The three irrigation treatments were: no-irrigation (No-I); irrigation to meet calculated evapotranspiration (ET) according to the Wisconsin Irrigation Scheduling Program (WISP); and irrigation to equal 3.8 cm (1.5 inches) of rainfall plus irrigation per week (ET+). Since the NO_3 leaching study is an add-on to an existing project, there was only one level of N fertilizer applied to the main irrigation blocks. The No-I block was split to give a control block with no N under rain-fed conditions. The sub-plot treatments were two types of tillage: moldboard low tillage (MB) and no-tillage (NT). Each tillage plot was split to accommodate sub-sub-plots with and without Acrysol ASE 108 polymer added to the herbicide tank mix.

The field research site was tilled and planted to corn on 29 April 1990 (day of year, DY 119). Starter fertilizer [112 kg/ha (100 lb/acre) 6-24-24] and 0.54 kg (1.2 lb) active ingredient/ acre terbufos (an insecticide) was applied at planting. After installation of monitoring equipment, herbicides were applied at recommended rates on 11 May 1990(DY 131). For the polymer treatments, Acrysol ASE 108 was added to the herbicide tank-mix and applied at a rate of 0.20 kg (1.1 lb) of polymer solids per hectare. Additional nitrogen fertilizer was applied as a sidedress of 213 kg N/ha (190 lb N/acre) of 24-0-0 urea ammonium nitrate (UAN) on 28 June 1990 (DY 179). Fertilization was limited to a single sidedress because field operations had to be limited to avoid damaging instruments in the field. The research plots were established in 1989. In this regard, sterile field corn was planted late so as not to conflict with adjacent seed corn production, but still allow for a corn-into-corn rotation for 1990. In 1989, 213 kg N/ha were applied and no corn grain or stover was harvested from the field.

The site consisted of 2.8-ha of level river valley mapped as a Sparta sand (Entic Hapludoll; 96% sand, <2% clay, and 0.8% organic matter). Four groundwater-monitoring wells were installed at the site in November 1989. Wells are located on the south, west, and north end of the field (Figure 1). Depth to groundwater is about 3 m (10 ft). Groundwater movement is in a north to north-westerly direction toward the Wisconsin River. Extensive site and soil characterization was performed in 1989 and 1990.

The plots were irrigated with a 95.4-m (313-ft) long linear irrigation system. Water was supplied to the irrigation system from an 18.3-m (60-ft) deep supply well constructed at the site in April 1990. The irrigation system was equipped with low-pressure spray nozzles that allow controlled, uniform water application.

A remote, automatically recording weather station was established at the site in 1989. The weather station collected data required for calculating irrigation schedules and for applying



Treatments

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

W irrigation well
● reference stake (permanent)
■ monitoring well (M1-M4)
field office
T time domain reflectometry (TDR) probes
✚ in-situ soil column

□ Neutron moisture-probe access tube (NMP)
◇ Porous-cup sampler (PCS)
PCS + NMP
○ Tensiometer nest (TN)
TN + NMP
TN + PCS + NMP

Figure 1. Schematic map of field research site, Arena, Wisconsin.

mathematical models to predict water and solute movement through the soil profile. Parameters collected at the weather station included solar radiation, air temperature, relative humidity, wind speed and direction, amount and intensity of rainfall and soil temperature.

Nitrate movement was monitored with a combination of porous-cup soil-solution samplers, soil core samples, and groundwater collected from monitoring wells. A total of 84 porous-cup samplers were installed at four depths: 25 cm (10 in); 60 cm (2 ft); 140 cm (4.5 ft); and 250 cm (8 ft). The 250-cm deep porous-cup samplers were not installed on the NT, polymer, or No-N plots. Soil solution samples were collected by placing a vacuum on the samplers after rainfall and irrigation. Soil cores were taken from the soil surface to 2.3 m (8 ft) at 5 (DY 155), 12 (DY 205), and 26.5 (DY 305) weeks after planting. Soil-water movement was monitored by a combination of tensiometers, a neutron moisture meter, and a time domain reflectometer (TDR). Concentrations of NO_3 in soil solutions collected in porous-cup samplers were determined by ion chromatography at the Soil and Forage Analysis Laboratory, Marshfield, Wisconsin. Field-collected soil cores were transported in an ice chest at 4°C to the Soil and Plant Analysis Laboratory, Madison, Wisconsin for chemical analysis.

Yield rows (9.1 m = 30 ft long) in each sub-plot were harvested by hand and shelled on 5 October 1990 (DY 278) to determine corn grain yields. The rest of the field was mechanically harvested on 15 October.

RESULTS AND DISCUSSION

RAINFALL AND IRRIGATION

Table 1 shows rainfall and irrigation totals from planting to the end of September, 1990 at the field research site. During May, rainfall was about 2.5 cm (1 inch) above-normal and by early August the LWRV had received about 10 cm (4 inches) more rainfall than is normal for a growing season. Figure 2 shows the rainfall and irrigation distribution for the No-I, ET, and ET+ blocks graphed with respect to days after herbicide application (subtract 48 to calculate days after N application). Several large rainfall events (≥ 2.5 cm, 1 inch) occurred throughout the growing season, with the largest event (6.8 cm) on the evening of the day N fertilizer was applied.

Table 1. Precipitation and irrigation, from 29 April to 29 September 1990 for the Arena field site.

Treatment	Rainfall	Irrigation †	Total
	------------------------ cm (inches)	------------------------	
No-I	50.6 (19.9)	0.0	50.6 (19.9)
ET	50.6 (19.9)	12.2 (4.8)	62.8 (24.7)
ET+	50.6 (19.9)	19.3 (7.6)	69.9 (27.5)

† First irrigation 6 July 1990 (day of year, DY 187); last irrigation 4 September 1990 (DY 247).

Over the course of the growing season, approximately 650 soil solution samples were collected and analyzed for NO_3. The samples were collected on 14 dates. On any particular sampling day, some samplers did not collect a sample. These samplers failed to collect water because of dry conditions, particularly in No-I plots, or because of equipment failure. Data are compiled from these 650 samples.

SOIL SOLUTION NITRATES

The relationships between NO_3-N concentrations in soil-water and time (days after application, DAA) have been plotted. The concentration of NO_3-N in the control plot (No-I, No-N) was approximately 20 ppm throughout the profile at the time of N application and showed erratic values for the next 140 days (Figure 3A). The NO_3-N soil solution concentrations increased at all depths in the 12 DAA of nitrogen as a result of a 6.78 cm rain that occurred on the day of nitrogen application, although overall N concentrations decreased at depths < 250 cm over time (as DAA

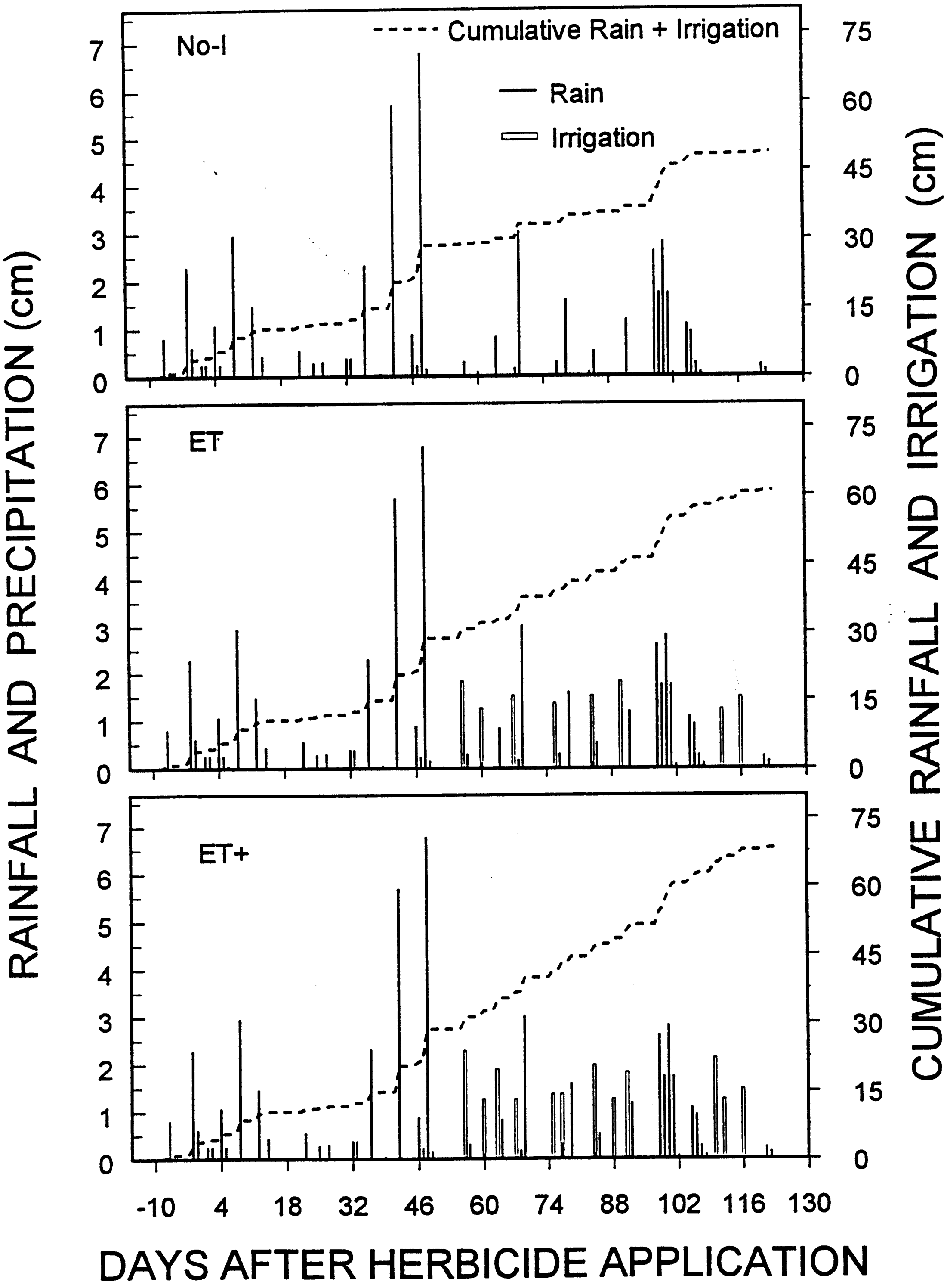


Figure 2. Rainfall and irrigation distribution for no-irrigation (No-I), irrigation to meet evapotranspiration (ET), and irrigation to exceed ET (ET+) blocks. Nitrogen application was on day 48.

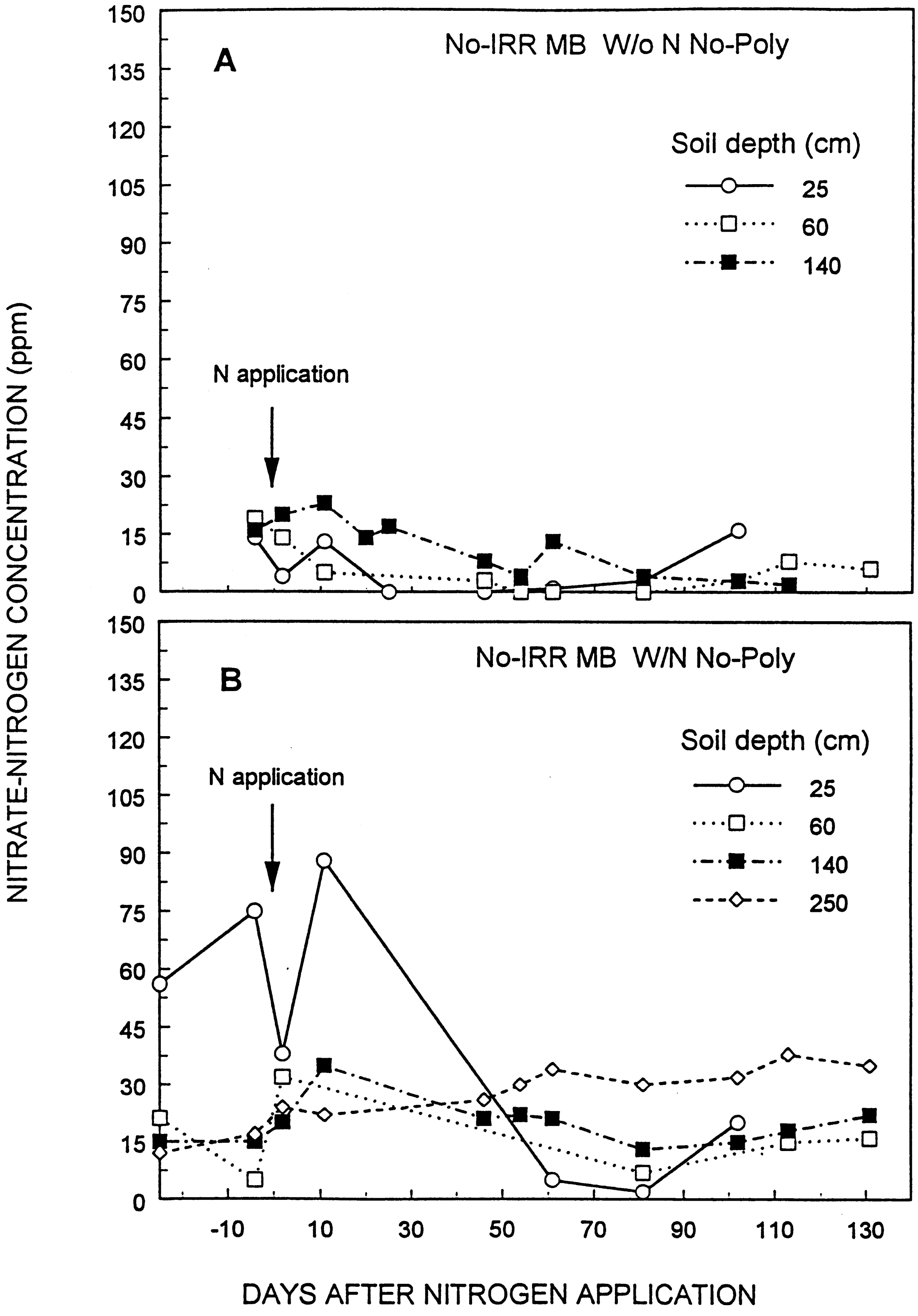


Figure 3. Soil solution NO_3-N concentrations (average of three treatment replications) for No-I, MB, no-polymer without nitrogen (A) and with N (B) graphed with time after N application.

progressed) (Figure 3B). The concentrations of NO_3-N in the fertilized blocks were consistently greater than those found in the corresponding depths of the blocks not receiving N. The general decrease, as time progressed, in the amount of NO_3-N present in the fertilized block at depths < 250 cm indicates rapid leaching of NO_3-N from the root zone. The greatest NO_3-N concentration (90 ppm) was measured in the No-I, MB, w/N treatment at the 25-cm depth 12 DAA (Figure 3B). This large concentration is attributed to N fertilization. If a calculation is made of the NO_3-N concentration expected in the soil water immediately following an application of 213 kg N/ha (190 lb N/acre), a value of 90 ppm appears reasonable.

The process used to calculate the expected concentration of soil-water NO_3-N is as follows: Approximately 24% of the urea ammonium nitrate-N was in the NO_3 form at the time of application. Therefore, a 213 kg N/ha (190 lb N/acre) application contains 51 kg NO_3-N/ha (46 lb NO_3-N/acre) (5,156 mg/m^2 or 479 mg/ft^2, assuming an even distribution). If this amount of NO_3 were dissolved in the amount of water in a 1 ha-cm of rainfall, the NO_3-N concentration would be approximately 200 ppm. If it were dissolved uniformly into the amount of water in a 2.75 ha-cm rainfall, the concentration would be about 75 ppm. In actuality, the mechanisms and processes active in the field are generally not this simplistic. For example, nitrification occurring during the 2 days between N-application and soil-solution sampling, as well as leaching of ammonium in this low CEC (2 to 3 meq/100 g soil) may decrease the amount of NO_3-N present in the soil. However, this calculation helps put the observed values into perspective.

The first irrigation of the season was applied 8 DAA (6 July 1990) of N. For the ET (Figure 4) and ET+ (Figure 5) treatments, the increase in NO_3-N concentration throughout the soil profile began immediately following the 6.78 cm (2.67 inch) rainfall event, prior to irrigation. There was more NO_3-N in the moldboard-plowed plots (Figure 4A) than the no-tillage treatments (Figure 4B) at the 25-cm depth prior to N application. This was apparently because of incorporation of plant residue from the previous crop into the soil profile by moldboard plowing.

Differences in the distribution of NO_3-N between MB and NT treatments in the plots receiving ET+ (Figure 5A, B) were less pronounced, probably because of increased leaching of NO_3-N caused by the higher rate of irrigation. Nitrate-N leached from the shallower depths quickly in the MB treatment, while NO_3-N in the NT treatments persisted longer at the 60-cm depth than in the MB treatment presumably because of the decreased amount of macropore flow in the NT system. The lack of NO_3-N at the 25-cm depth in the NT treatment initially is likely a sampling error.

Comparing the No-I (Figure 3A) to the ET (Figure 4A) and the ET+ (Figure 5A) treatments, the concentration of NO_3-N in the root zone (<1.5 m) decreases faster in the irrigated treatments relative to the No-I treatment. By 50 DAA of NO_3-N (17 August 1990), the concentrations in the <1.5-m zone in irrigated plots are <10 ppm. This was because of more vigorous plant growth and/or increased leaching in the irrigated treatments.

After N was applied, there were elevated NO_3-N concentrations at the 250-cm depth. There was 35 ppm NO_3-N at the 250-cm depth until late into the growing season (October), indicating a high possibility of groundwater contamination by NO_3-N because of the shallow depth to groundwater (300 cm).

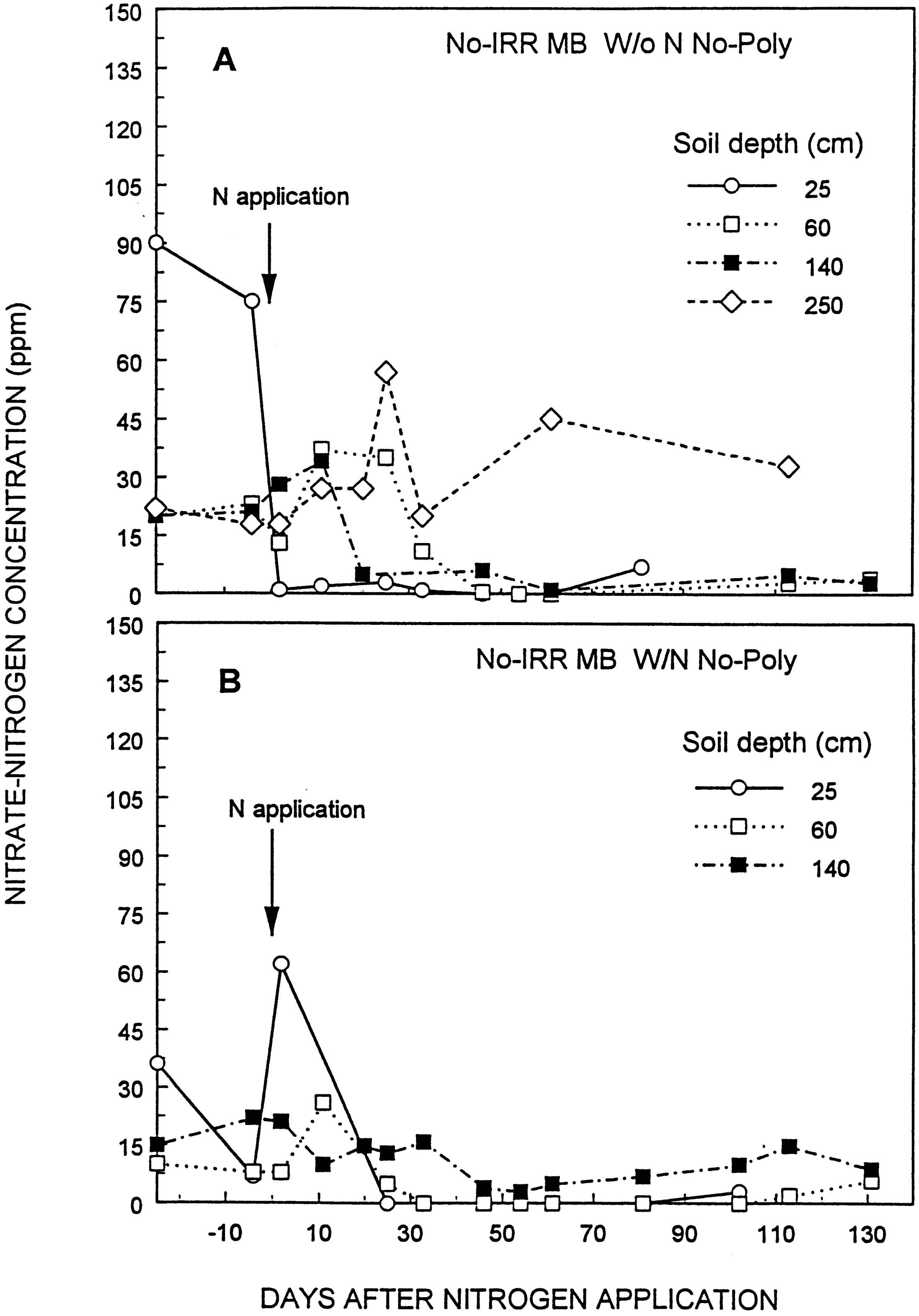


Figure 4. Soil solution NO_3-N concentrations (average of three treatment replications) for ET, MB (A) and NT (B) no-polymer treatments LWVR-Arena project, 1990.

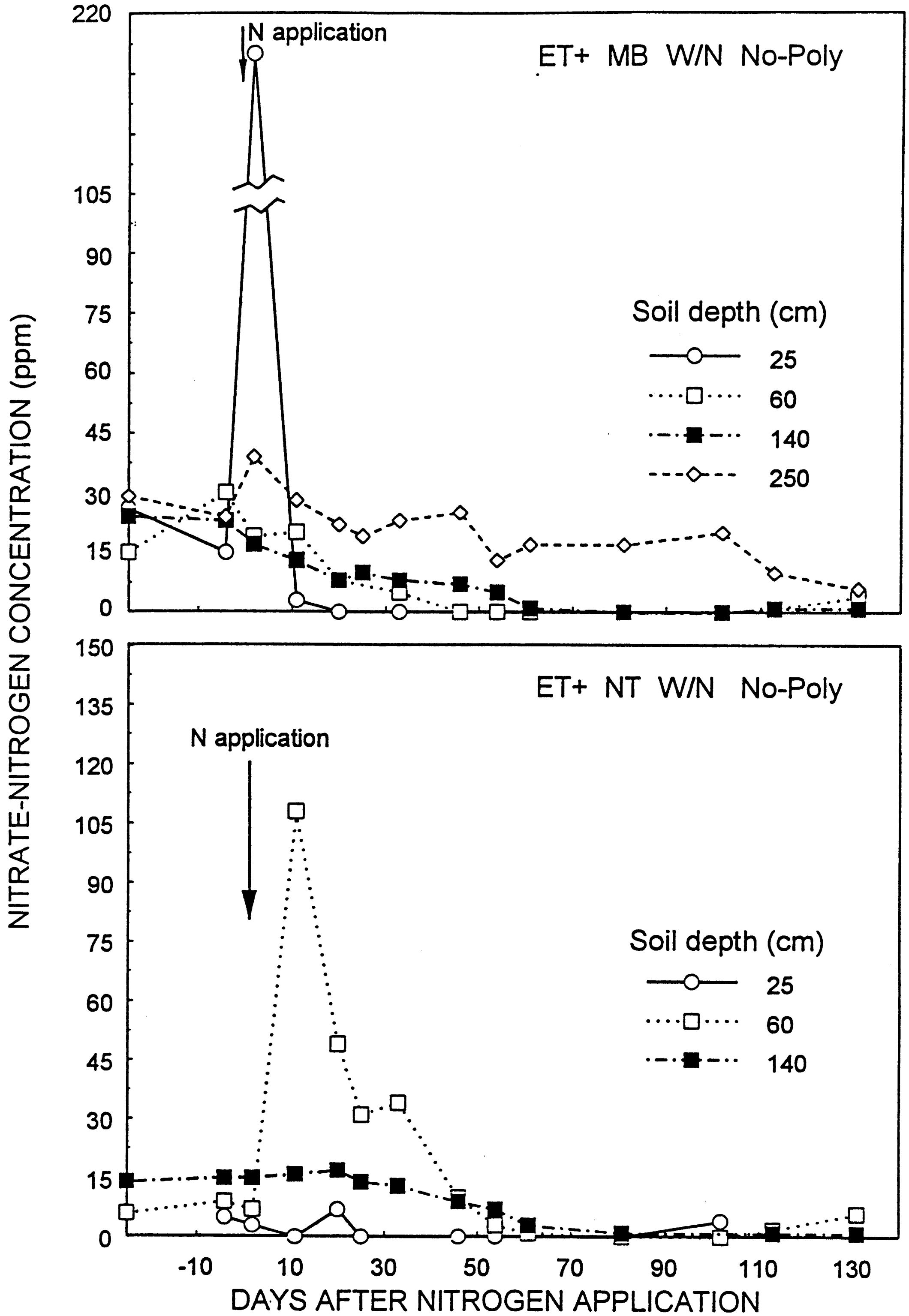


Figure 5. Soil solution NO_3-N concentrations (average of three treatment replications) for ET+, MB (A) and NT (B) no-polymer treatments LWVR-Arena project, 1990.

The distribution of nitrate in the soil profile for selected times during the growing season are shown in Figure 6 (ET treatment) and Figure 7 (ET+). For both irrigation treatments, the concentration of NO_3-N in soil-water at all depths was <25 ppm 3 days before N fertilization. A significant response to N application was measured 2 DAA at the 25-cm depth in the MB ET+ treatment (Figure 7B), but the N from fertilization was not captured in the MB ET treatment (Figure 6B). Between 2 and 20 DAA of N, the first irrigations were applied, with the ET+ block receiving about 2.54 cm (1 inch) more water than the ET block. This "extra" water may partly explain the lesser concentrations of NO_3-N in the soil-solution in the ET+ relative to the ET treatment, especially at the 60-cm (2-ft) depth (Figures 6C and 7C). At 60 DAA, very little NO_3-N remained in the root zone of either irrigation treatment; however, measurable increases in NO_3 were recorded at 250 cm (Figure 6D).

Measurements of soil water using a neutron meter and TDR indicated no obvious differences in NO_3-N movement between polymer-treated soil and untreated soil (Figure 8).

GROUNDWATER MONITORING DATA

The four groundwater monitoring wells (Figure 1) were sampled six times in 1990-91. Nitrate-N analyses were performed on samples collected on the last five sampling dates (Table 2). The 31 May sampling time was 1 month before nitrogen fertilization and the 12 September, 14 November, 26 March, and 5 June samplings were 76, 139, 271, and 342 days after N application, respectively. As indicated in Figure 1, groundwater flow beneath the plot is from the southeast corner to the northwest corner. The upgradient well, MW-4, consistently showed low levels of NO_3-N. The well with the high concentration of NO_3-N was MW-1, screened at 3 to 4.6 m (10 to 15 ft) below the water table. This well also contained the greatest concentrations of atrazine (data not included). Prior to fertilization, the groundwater beneath the site was stratified with "clean water" over water containing high concentrations of NO_3-N and atrazine.

Table 2. Nitrate-N in groundwater of LWRV-Arena Project, 1990-91.

Sample date	Nitrate-N concentration (ppm)				
(day of year)	MW-1 †	MW-2	MW-3	MW-4	IRR-1
20 March 1990 (79)	--	--	--	--	--
31 May 1990 (151)	14.8	2.9	5.0	1.5	--
12 September 1990 (255)	13.0	18.2	6.6	0.4	8.4
14 November 1990 (318)	15.2	17.6	6.1	0.8	8.8
26 March 1991	17.5	21.8	6.47	0.82	8.8
5 June 1991	19.0	21.7	4.01	3.56	9.1

† MW-1 is screened at 3 m (10 ft) below the water table; IRR-1 is screened at 9.1 to 15.2 m (30 to 50 ft) below the water table. All other wells are screened at the water table. IRR-1 is a deep well -- 60 feet (18 m).

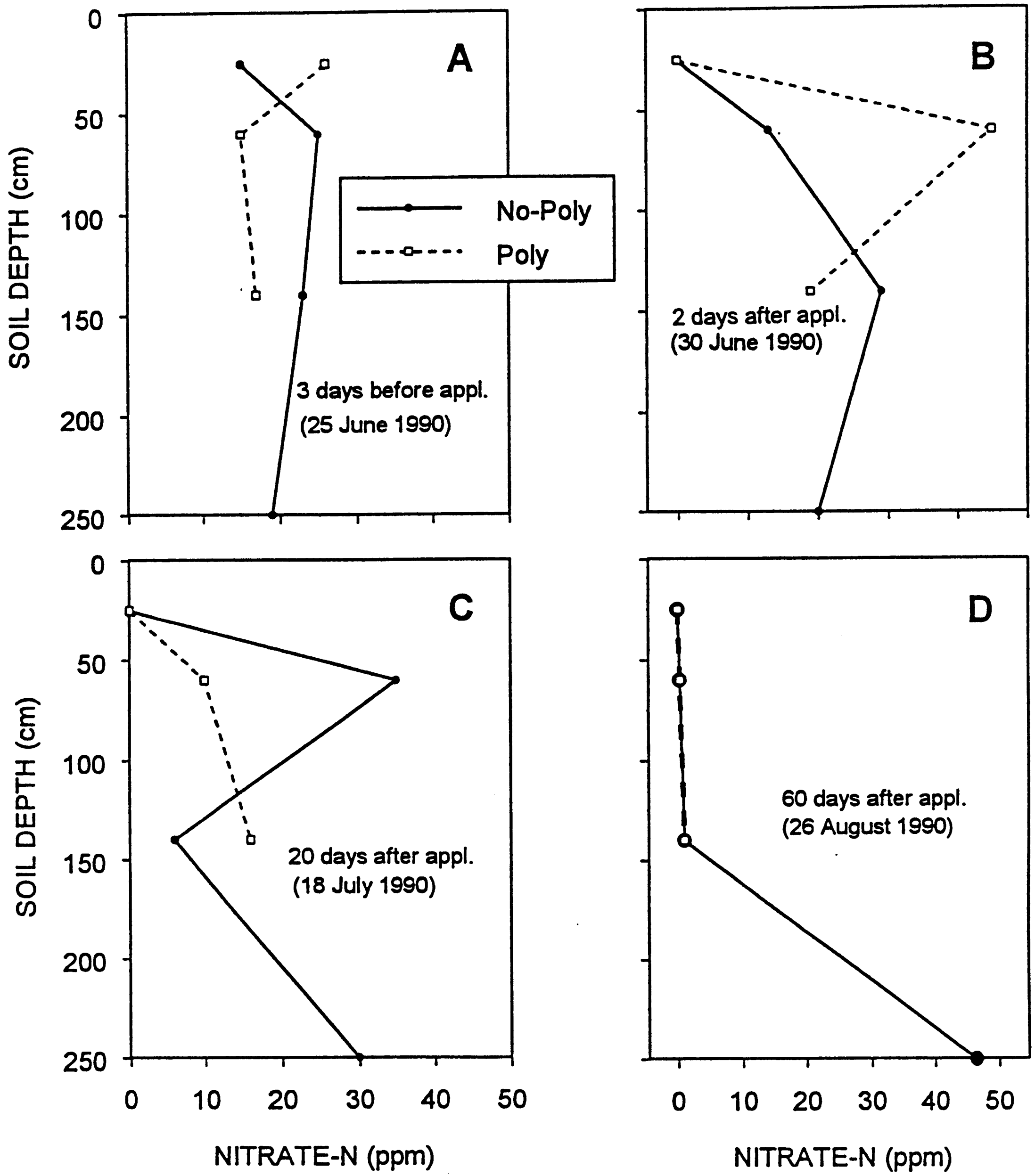


Figure 6. Soil solution NO_3-N distribution for ET, MB treatments 3 days before (A) and 2 (B) 20 (C), and 60 (D) days after nitrogen application.

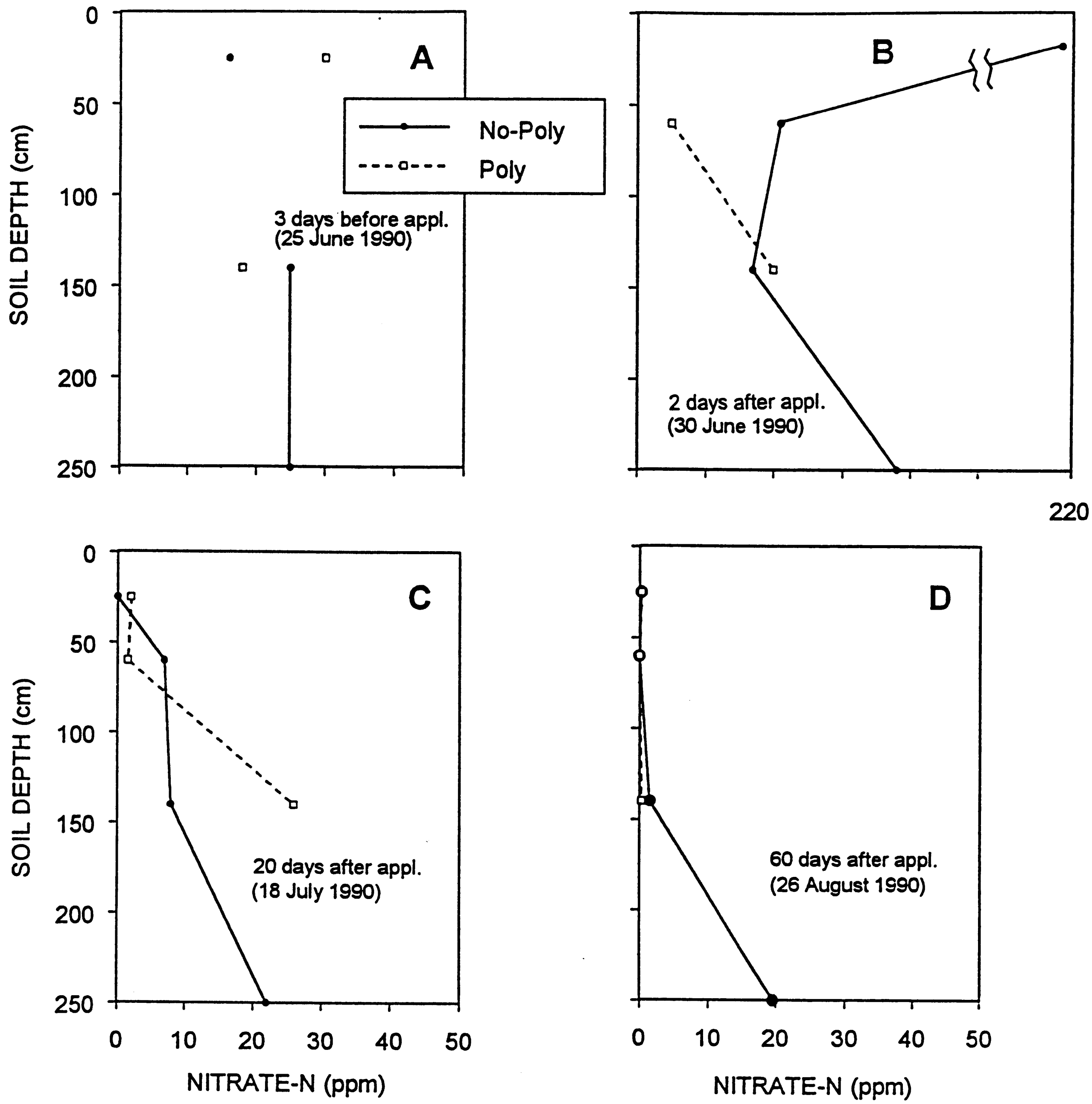


Figure 7. Soil solution NO_3-N distribution for ET+, MB treatments 3 days before (A) and 2 (B) 20 (C), and 60 (D) days after nitrogen application.

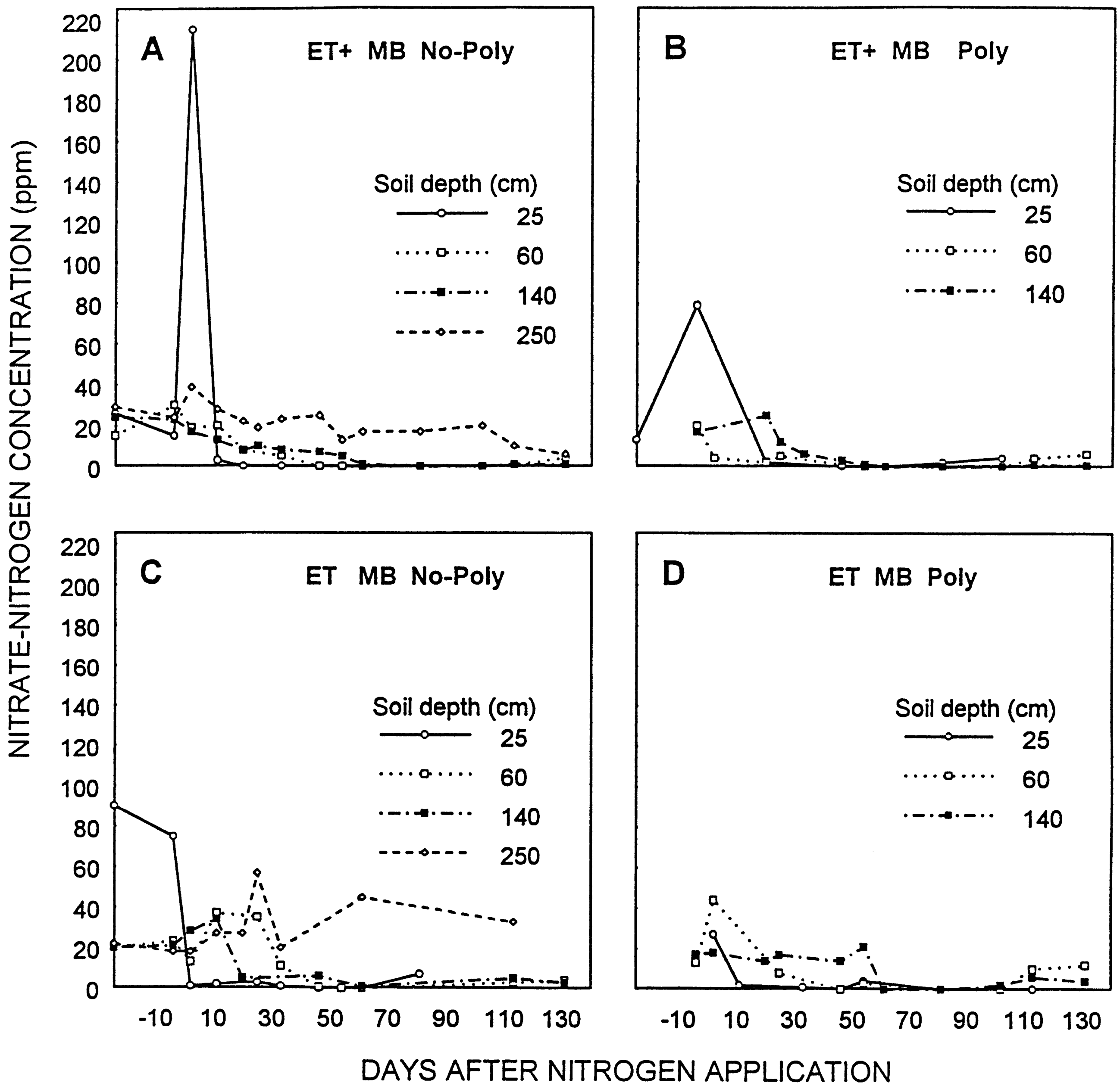


Figure 8. Comparison of soil solution NO_3-N concentrations (average of three treatment replications) for ET+ (A and B), and ET (C and D) no-polymer (A and C) and polymer (B and D) treatments.

After N application, there was a significant increase in NO_3-N concentration in MW-2 immediately adjacent to the north end of the plots. All buffer areas received N fertilization at 222 kg/ha (200 lb/acre) 2 days prior to N application to the research plots. The large rainfall immediately following application along with the short travel distance from site of application to MW-2 is probably the reason for the sharp increase in groundwater NO_3-N. Progressive increases in NO_3-N concentrations after 12 September suggest that groundwater containing N was being displaced into the deeper part of the aquifer with new recharge.

1990 CORN YIELDS

Corn-grain yields are presented in Table 3. Irrigation resulted in higher yields than were obtained in the non-irrigated plots. As expected, yields were much lower when N was not applied. In general, yields were greater in the NT than the MB treatments, which may result from the increase in soil moisture content and/or a decrease in wind erosion damage in the NT plots. Polymer treatments resulted in greater yields in the NT plots; however, the presence of polymers had no effect on corn yield in the MB systems. Reasons for the polymer treatment differences are not known. However, an interaction with nitrogen is suspected, but is not clearly substantiated by nitrate leaching data.

Table 3. Corn grain yield, 1990, LWRV-Arena Project.

	Moldboard plow tillage		No tillage	
Treatment†	No polymer	Polymer‡	No polymer	Polymer
	mg/ha (bu/acre)			
ET+	a 6.77(108)a*	a 7.90 (126)a	a 7.46(119)a	a 9.85(157)b
ET	a 6.46(103)b	a 7.15(114)ab	b 6.08 (97)b	b 7.65(122)a
No-I	b 3.70 (59)a	b 3.95 (63)a	b 5.27 (84)b	c 4.58 (73)b
No-I No-N	c 1.51 (24)a	c 1.32 (21)a	c 2.01 (32)a	d 1.69 (27)a

* 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.

† 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.

CONCLUSIONS

Rainfall was greater than normal during the 1990 growing season and several large storms caused deep percolation of water and NO_3-N. The largest storm (6.78 cm) occurred immediately following nitrogen fertilizer application, creating a worst-case scenario with respect to nitrate leaching. Sampling equipment located 250 cm (8 ft) below the soil surface indicated that significant amounts of fertilizer N were leached below the root zone. We anticipate linking water flow and NO_3-N concentration measurements to estimate total nitrate leaching losses. It is clear from this study that a significant amount of the nitrogen, applied as fertilizer, can leach to the shallow groundwater beneath sandy soils in the LWRV. However, the amount of N that eventually reaches groundwater is a function of application rate and time of application. We found the amount of N leaching is also a function of the amount of water supplied (as irrigation or rainfall) relative to fertilizer application.

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