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Groundwater Contamination from Fertilizer Nitrogen[1]

by

Harold R. Duke[2], Darryl E. Smika[3] and Dale F. Heermann[4]

INTRODUCTION

With increasing pressure on water supplies of the west, concern continues to grow over protection of both quantity and chemical quality of water resources. Until recent years, neither environmental concern nor economic incentive have been sufficiently great to compel careful management of water and fertilizers under irrigated agriculture. Numerous studies (Smika, et. al., 19[illegible], Edwards, et. al., 1972, Stewart, et. al., 1968) have indicated that nitrogen fertilizers are leached beyond the crop root zone by excessive irrigation. The consequences of excessive levels of nitrite in potable water are widely recognized.

Widespread acceptance of the center pivot irrigation system has resulted in recent development of literally millions of acres of previously unirrigable lands. The sandy soils to which these systems are so well adapted have a very low water holding capacity, typically 4 to 5 inches (10 to 12 cm) available water through the entire root zone. This low storage capacity, coupled with high hydraulic conductivity allows rapid percolation of excess water. Because nitrate fertilizers in particular are quite soluble, the potential exists for leaching large amounts of NO_3-N toward the water table.

These unique soil characteristics and the practically unattended operation of the center pivot sprinkler system present problems of irrigation management quite different from those of conventional irrigation on heavier soils. We

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initiated intensive field studies in 1972 to evaluate the effects of irrigation water management on crop yields and nitrate nitrogen losses from the crop root zone. In 1974, the studies were expanded to study subsequent movement of water and nitrates toward the water table. This paper presents a partial analysis of the results of these studies.

STUDY AREA

The area selected for these studies lies in the northeastern corner of Colorado, near the community of Crook, in the alluvial valley of the South Platte River. The soils north of the river are fine textured and have been irrigated for practically a century. South of the river, however, the soils are fine sands, and for the most part remained native rangeland until the center pivot sprinkler came into general use. Many center pivot sprinklers are operated by farmers who formerly irrigated the heavier soils north of the river.

By the mid 1960's, development of this sandy rangeland with center pivot irrigation was significant, and continues to increase. The water supply is from the shallow alluvial aquifer. The average annual precipitation is approximately 14 in (355 mm) with half or less occurring during the growing season. Practically all the acreage under center pivots in this area is planted to corn (*Zea mays* L.). Unless precipitation is especially favorable, irrigation will begin soon after planting in late April or early May and continue until mid-September or later. Because the soils have very low available-water-holding capacities, there is little soil water storage to support the crop for extended periods without irrigation. To allow for the possibility of mechanical failure, most operators run the irrigation system nearly continuously in an attempt to maintain the soil profile as nearly full of water as possible. As a result, excess water is frequently leached beyond the root zone, and may carry soluble fertilizers toward the water table.

Four farmer-owned and -operated center pivot sprinkler systems were studied in this area. One system (designated "C") was used to apply liquid fertilizer and could not apply less than 0.8 in (20 mm) water per irrigation. Irrigations with system "C" were scheduled by the farmer. Systems "A", "B" and "D", operated by a different farmer, were scheduled using the USDA Irrigation Scheduling Program (Heermann, Haise and Mickelson, 1976). All fertilizer for the latter three systems was applied directly to the soil. During early irrigations when the root system was shallow about 0.6 in (15 mm) of water was applied per irrigation. Systems "A", "B", and "C" have been under irrigation since 1965, while system "D" was first broken from rangeland and irrigated in 1974. Thus, these three systems allowed evaluation of the influence of irrigation on the soil profile over a range of irrigation history covering thirteen seasons.

EXPERIMENTAL PROCEDURES

Each of the four circles was instrumented to attempt to measure directly all components of the water budget during the growing season. A climatic station was established within the irrigated area, located to have as much fetch as possible across irrigated cropland. This station included a pyranometer, anemometer, recording raingage, hygrothermograph, and maximum and minimum thermometers. The data collected were used as input to the USDA Irrigation Scheduling Program as modified by Heermann (Heermann, et. al., 1976) to calculate potential evapotranspiration. Hydraulic lysimeters, similar to those described by Hanks and Shawcroft (1965) were installed within circles "B", "C", and "D" to check the crop coefficient curves for the local area. After calibrating the model, the computer program was used for subsequent calculation of the evapotranspiration (ET) component. Further checks of the ET calculation were made periodically by soil moisture measurement using the neutron scattering technique.

Vacuum extractors (Duke and Haise, 1972) were installed beneath each circle to measure deep percolation beyond the root zone. This device consists of a soil filled metal trough with porous-ceramic tubes in the bottom. The trough is buried below the crop root zone, with the open side up. A vacuum is continuously applied to the ceramic tubes to intercept percolating water for subsequent volumetric and chemical analysis. Three extractors were installed beneath each of fields "A", "B", and "C" and six beneath field "D."

Water samples for NO_3-N analysis were collected periodically from each of the vacuum extractors, from the irrigation wells, and from stock wells up gradient from the irrigated area. In addition, five observation wells and two banks of piezometers were installed within and immediately adjacent to the irrigated area. The piezometer banks consisted of four piezometers each, perforated at two foot (60 cm) intervals beginning about 1 foot (30 cm) below the average water table. Samples collected from the piezometers were used to evaluate vertical concentration gradients in the groundwater. Further evaluations of NO_3-N concentration and movement were made from periodic soil samples collected within the root zone and from deep cores to 30 ft (10 m).

Experiments under circles "A", "B", and "C" were designed to evaluate the results of optimum water management on deep percolation losses. Each field was managed as a single treatment, with fields "A" and "B" irrigated according to the computer schedule and field "C" scheduled by the farmer. The irrigation system on field "D" was fitted with additional sprinkler heads at two locations as shown in Figure 1. These additional heads were turned on over a sector of

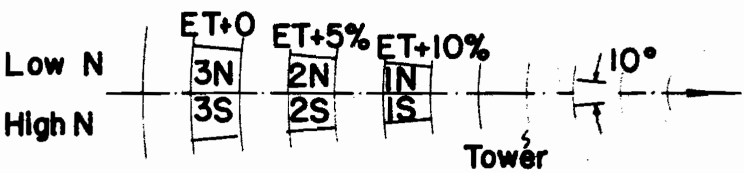

Figure 1. Plot locations for water and fertilizer management studies, field "D."

approximately 10°. Three water treatments, intended to apply 0, 25 percent, and 50 percent excess irrigation were applied to field "D." In addition, each water treatment was divided into two subtreatments, with an excess of 150 lb/ac (168 kg/ha) N fertilizer applied to one subplot of each treatment. Total water application (irrigation and precipitation) was measured at each site, using rectangular raingages of 251 in^2 (1620 cm^2) area. These gages, which averaged the catch over a 48 in (1.22 m) length along the radial, were supported at the top of the crop canopy throughout the season.

RESULTS

Water Management. Comparisons of farmers' irrigation practices (field "C" and early studies on "A" and "B") with computer scheduled irrigation (fields "A", "B" and "D") indicate that water applied by the farmer could be reduced by 5 in (130 mm) annually or approximately 20 percent by computer scheduling. During the period 1974-1976 when fields "A" and "B" were irrigated according to the computer schedule, corn grain yields increased from a pre-scheduling average of about 8000 lb/ac (8960 kg/ha) to a 3 year average of 9800 lb/ac (11,000 kg/ha). Because of varietal differences, climate, and changes in other farm management practices, the increased yield cannot be entirely attributed to better irrigation management.

That excessive irrigation adversely affected the overall management program is apparent from the measured NO_3-N in the leachate from field "C." Rotational speed of that system could not be increased to provide smaller water applications. Because all the N fertilizer was applied through the irrigation system, a full irrigation was required to supply needed fertilizer, even when the soil profile was filled with water. This resulted in excessive percolation of both N and water.

Results of the water treatments under field "D" are shown in Table 1. Actual excess irrigation application was complicated by significant precipitation during the growing season. Total water applications were approximately 10, 5 and 0 percent greater than ET estimates. Although no statistically significant differences in

Table 1. Summary of annual average water application during the growing season and yield under water treatment plots, field "D" (10 June through 5 September, 1974-1976)

	Plot		
	1 (ET + 10%)	2 (ET + 5%)	3 (ET + 0)
Precipitation, in. (mm)	4.80 (122)	4.87 (124)	4.79 (122)
Irrigation, in. (mm)	20.34 (517)	18.67 (474)	17.53 (445)
Calculated evapotranspiration, ET, in. (mm)	22.98 (584)	22.83 (580)	22.65 (575)
Excess application, %	9.4	3.1	-
Grain yield, lb/ac (kg/ha)	8634 (9677)	9244 (10360)	8694 (9744)

grain yield can be shown, the effects of excess irrigation on the nitrogen profile are obvious, as will be discussed in a succeeding section.

Development of the Soil NO_3-N Profile. Experiments on field "D" were begun when the field was first put under cultivation in 1974. At that time, there was an insignificant amount of nitrogen in the upper soil profile, approximately 0.07 ppm or 1.7 lb/ac (1.9 kg/ha) total in the upper 6 ft (1.8 m) of soil. (Nitrate nitrogen distribution under a similar rangeland site is shown in Figure 4).

The low N level plots in field "D" received 210 lb/ac (235 kg/ha) N, primarily as ammonia, during each year of the study. In addition to that level of fertilization, the high nitrogen level plots received 50,100, and 0 lb/ac (56, 112, 0 kg/ha) in 1974, 1975 and 1976 respectively. Figure 2 illustrates the NO_3-N concentration profile under the low N level where water was applied only as needed by the crop. Following the 1975 growing season, a soil buildup of NO_3-N was evident. At this time, however, the fertilizer had not moved beneath the root zone. By the end of the third growing season, the total NO_3-N within the root zone was somewhat reduced and the peak concentration had moved below the root zone. Approximately 60 lb/ac (67 kg/ha) NO_3-N remained in the 6 ft (1.8 m) root zone.

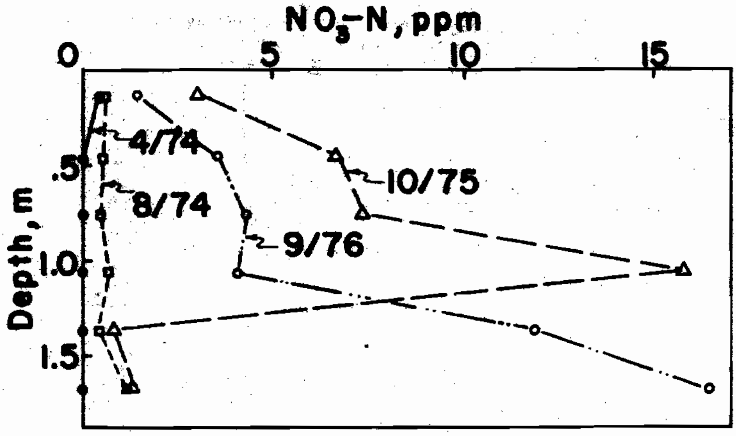

Figure 2. Nitrate-nitrogen concentration in saturated extract from field "D", low nitrogen and low water (ET + 0) levels (plot 3N).

Figure 3 shows very low post-season NO_3-N concentrations when approximately 10 percent excess water was applied, even on the plot receiving excessive

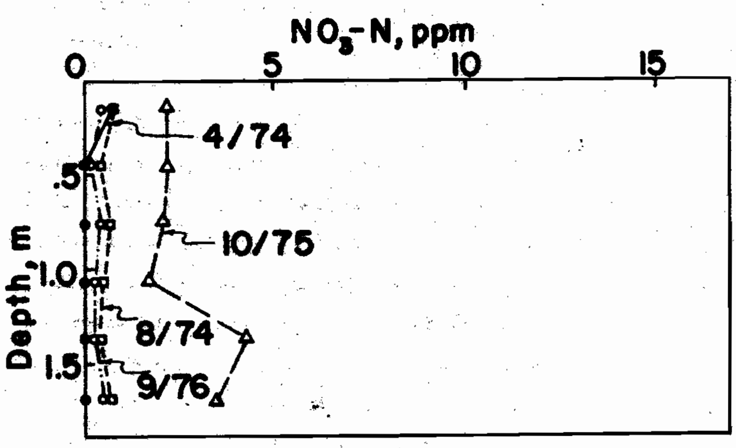

Figure 3. Nitrate-nitrogen concentration in saturated extract from field "D", high nitrogen and high water (ET + 10%) levels (plot 1S).

fertilizer application. The 100 lb/acre (112 kg/ha) extra N applied in early 1975 did result in an increased concentration at the bottom of the root zone by the end of that season. However, excessive irrigation during the subsequent season reduced the carryover of NO_3-N to 10 lb/ac (11 kg/ha), practically as low as the native rangeland.

Figure 4 shows the increase in NO_3-N in the entire soil profile as a result of extended irrigation. As mentioned earlier, the native rangeland has practically

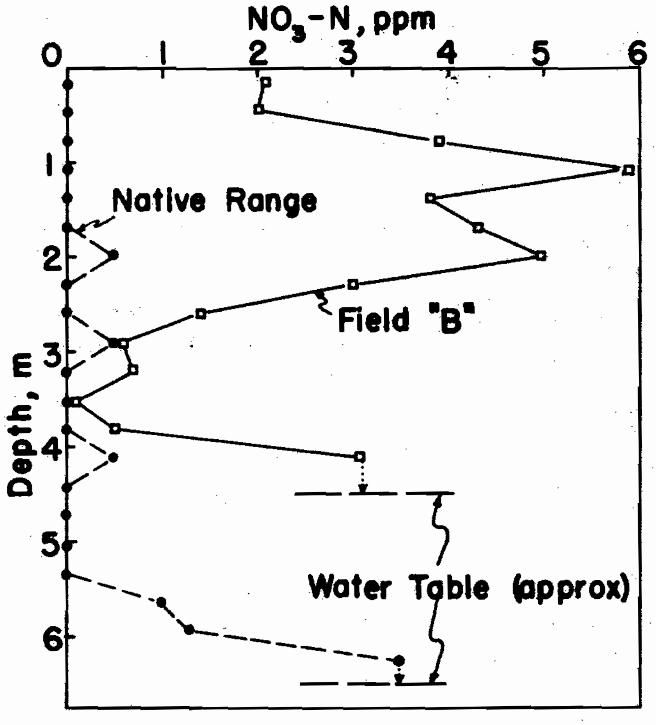

Figure 4. Nitrate-nitrogen concentration in deep soil profiles, July 1976.

no NO_3-N except in the capillary fringe above the water table. Following twelve years of irrigation, the concentrations are relatively high in the upper 8 ft (2.5 m). In the lower profile, however, NO_3-N concentration is little different than under the native rangeland. Smika, et. al. (1977) reported leaching of soil NO_3-N by winter precipitation and early spring irrigation. This leaching is apparent from Figure 4 also, as two concentration peaks, at 3.5 and 7 ft (1.0 and 2.1 m), are quite evident. The lower of the two peaks represents NO_3-N leached below the root zone following the previous growing season.

Percolate Losses of NO_3-N. Water samples from each of the vacuum extractors were collected weekly for NO_3-N analyses. These analyses and measured volumetric flux allowed calculation of seasonal total NO_3-N percolation. Table 2 provides a summary of the 3 year average water and NO_3-N percolate losses for the four study fields. Obviously, total NO_3-N loss is directly related to the volume of deep percolating water. With a finite source of NO_3-N, however, dilution of concentration at high percolation rates is inevitable as for field "C." It is expected

Table 2. Summary of 3-Year Average Deep Percolation Losses

Field	Water		NO_3-N	
	in.	(mm)	lb/ac	(kg/ha)
"A"	0.74	(19)	27	(30)
"B"	0.46	(12)	17	(19)
"C"	2.86	(73)	53	(60)
"D" (ET + 0)	0.02	(0.5)	0.1	(0.1)

that the NO_3-N loss from "D" (ET + 0) will continue to increase, as nitrate was first detected in the percolate near the end of the 1976 irrigation season beneath this newly irrigated field.

The relation between annual depth of percolate and mass of NO_3-N loss is also illustrated in Figure 5. A considerable amount of scatter is expected in these

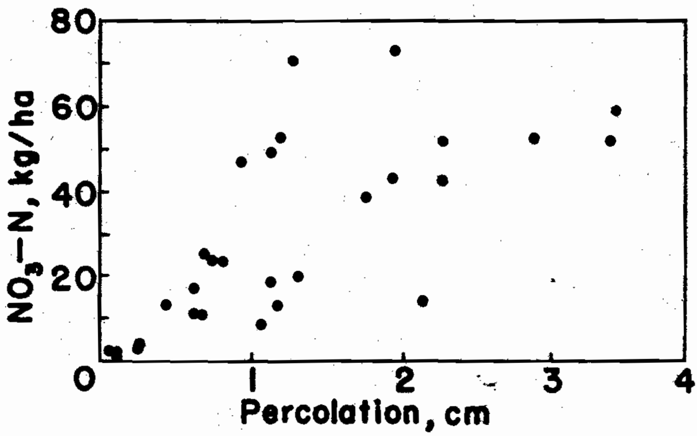

Figure 5. Annual NO_3-N leaching loss as related to annual deep percolation, all fields.

data since both rate of percolation and concentration of NO_3-N vary with time, soil variability and water application. Nevertheless, the point is made that proper water management will also affect management of nitrate losses.

Nitrate in Groundwater. Although it has been shown that overirrigation can result in leaching significant amounts of NO_3-N beyond reach of the crop roots, the ultimate disposition of that nitrate is less clearly understood. The fact that nitrate often appears in return flow from irrigated land is well documented (Edwards, et. al., 1972; Stewart, et. al., 1968). The relationship between water management and nitrate in groundwater is not.

Figure 6 shows the mean concentration of NO_3-N observed in one bank of piezometers adjacent to field "A." The concentration is nearly 50 ppm near the water table, decreasing rapidly with depth below the water table. The water pumped for irrigation, which represents an integrated value throughout the aquifer, has a NO_3-N concentration of approximately 4 ppm. Such high concentrations near the

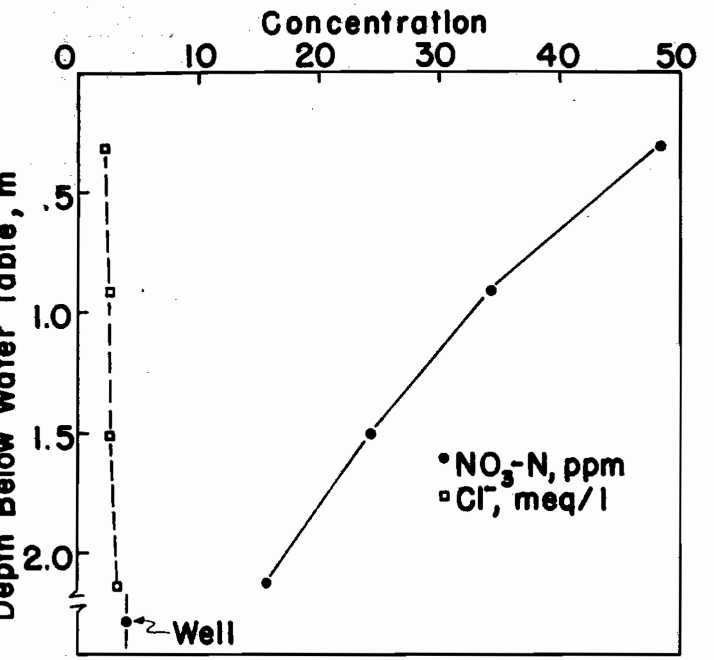

Figure 6. Nitrate-nitrogen and chloride concentrations in groundwater, mean of all samples.

surface have been observed by other investigators, and are sometimes attributed to percolating water "floating" atop the regional groundwater. However, this appears to be an improbable explanation if one considers the chloride concentration profile, also show in Figure 6. Even near the water table, the Cl^- concentration is less than 3 meq/ℓ, and is practically constant with depth. Average Cl^- concentration in the water pumped onto field "A" was 1.7 meq/ℓ (S_x=1.01) and that in the South Platte River some 2000 ft (600 m) distant is 3.9 meq/ℓ. The average concentration in the percolate from field "A" was 12.6 meq/ℓ, thus indicating that high Cl^- concentration should be observed near the water table if percolating water does indeed "float" on the regional groundwater.

A more plausible explanation appears to be the denitrification of NO_3^- in the anaerobic region in the vicinity of the water table. Such denitrification is usually attributed to microbial activity within the anaerobic region. However, support of denitrifying bacteria requires a source of organic carbon as a microbial energy source. The presence of this carbon source is as yet unverified and may be questioned because of the depth at which this denitrification apparently takes place. The water table at the piezometer bank of Figure 6 is 4 to 6 ft (1.2 to 1.8 m) below the surface. However, the same shape of groundwater NO_3^- profile was observed at water table depths to 20 ft (6.1 m).

Buresh and Moraghan (1976) present another mechanism of nitrate reduction. These authors showed that ferrous iron present in the anaerobic region of the aquifer can reduce NO_3-N directly to N_2.

Further analyses are underway to determine whether either sufficient organic carbon or ferrous iron are present at these sites to effect significant denitrification.

SUMMARY AND CONCLUSIONS

It has been shown that excessive irrigation of the sandy soils to which center pivot sprinklers are adaptable can result in leaching of significant amounts of nitrogen fertilizer as NO_3^-. Careful water management is an effective means of controlling NO_3-N losses. The USDA Irrigation Scheduling Program has been used successfully to determine the timing and amount of irrigation necessary to maintain high crop yields yet minimize leaching losses.

Although significant NO_3-N losses were measured from fields in the study area, neither the fraction of that NO_3^- present in return flows nor the mechanism of possible denitrification has been identified. If, in fact, significant denitrification occurs in the vicinity of the water table as current data suggest, the potential for groundwater pollution by leached nitrates is considerably reduced. Even so, careful water management remains an important factor in the irrigation program as it affects efficiency of fertilizer utilization, cost of energy for pumping, and ultimately the yield of crops produced.

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