METHODS FOR MONITORING LEACHATE LOSSES UNDER IRRIGATED CORN BEST MANAGEMENT PRACTICES

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ABSTRACT

Leaching of applied agricultural chemicals is a process which must be fully understood if we are to reduce agriculture's impact on the environment. A Best Management Practices (BMP) project was initiated in 1989 near Oakes, ND. A primary objective of the study was to develop and evaluate methods for measuring leachate losses from a corn (*Zea mays L.*) root zone. Lysimeters and subsurface drains are instrumental in understanding how our management practices affect movement of agricultural chemicals through the soil and into the ground water. Twenty undisturbed soil core lysimeters and four reconstructed lysimeters were constructed at the BMP quarter section. Construction of the undisturbed lysimeters consisted of collecting a large soil core in a PVC tube and instrumenting the bottom with a leachate collection system. The reconstructed lysimeters were large steel tanks filled with previously excavated soil layers. The large cores and tanks were replaced below grade so normal farming practices could continue. Leachate quality and quantity data is reported for the 1990 through 1995 growing seasons. Average undisturbed lysimeter leachate nitrate-nitrogen has decreased from 124 mg L^{-1} in 1990 to 8 mg L^{-1} in 1995. The disturbed lysimeter leachate nitrate decreased from 55 mg L^{-1} in 1990 to 4 mg L^{-1} in 1995 after peaking at 80 mg L^{-1} in 1991. Two subsurface drains underlying the BMP quarter serve as another method of quantifying leachate losses. In contrast to the lysimeter leachate nitrate concentrations, the average effluent nitrate for all drains rose from 3 mg L^{-1} in 1990 to approximately 5 mg L^{-1} in 1992 through 1994 and then dropped slightly in 1995. The subsurface drains are much more responsive to large precipitation events. Rapid increases in drain effluent nitrate following large precipitation events may be related to depression-focused recharge in areas of the BMP quarter section. Leachate data collected at the BMP quarter section indicate that irrigation and fertilizer BMPs do work to reduce ground water contamination.

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INTRODUCTION

In order to minimize agricultural impacts on ground water resources, we must be able to quantify the leaching of applied agricultural chemicals. A primary objective of a BMP study near Oakes, ND was to develop and evaluate methods for measuring leachate losses from an irrigated corn root zone. Use of lysimeters is a proven method for measuring movement of water and chemicals through the soil profile. For the BMP project, two different types of lysimeters were employed; undisturbed and disturbed profile lysimeters. In order to allow normal cropping practices to continue directly over the top of the lysimeters, a variation of existing methods was needed to obtain undisturbed soil cores as well as disturbed soil profiles for the study reported here. A subsurface drainage system was also used to monitor leachate at the unsaturated and saturated zone interface.

Lysimeters containing an undisturbed column of soil are desirable in that the leaching characteristics of the soil will generally be unaltered. A number of methods for obtaining undisturbed soil monoliths have been used, ranging from excavating around a column of soil and encasing it in a steel box (Brown et al., 1974), pressing steel cylinders over an exposed soil column (Brown et al., 1985), to using a static load to force large steel cylinders into the soil (Tackett et al., 1965).

Some type of leachate collection system must also be installed in the lysimeters after the undisturbed soil core is obtained. The simplest method for collecting water draining from a lysimeter tank is to simply attach a drain pipe to a hole in the bottom of the lysimeter. Although simple, this gravity drainage can only occur when the soil above the drain exceeds field capacity. In some situations, this can be an undesirable situation.

To more closely represent an uninterrupted soil column at the point of leachate collection, a vacuum extraction device has been installed in a number of studies. Tension plates (Cole, 1958) and ceramic suction cups (Wagner, 1962) have been employed to extract leachate samples. A vacuum trough extractor described by Montgomery et al. (1987) and first introduced by Duke and Haise (1973) extracted leachate samples without a convergence of flow often seen with ceramic cups.

Disturbed profile lysimeters differ from undisturbed lysimeters in that the soil contained in the tank is not an intact soil column but has been refilled after instrumentation has been installed. Montgomery et al. (1987) describe the construction of a disturbed profile lysimeter. In this case, a slotted plastic drain was installed in a gravel envelope at the bottom of the lysimeter and a vacuum extractor system installed during profile reconstruction. The reconstruction involved water working each restored soil layer back to its original density.

Subsurface drains have been employed for many years to lower water table elevations to improve cropping conditions and remove excess water. Drainage systems have been monitored for their effluent quality in an attempt to quantify the amount of applied chemicals leaching past the crop root zone and entering the ground water. Kladivko et al. (1991) studied losses of pesticides and nutrients under field conditions through subsurface drains. Their findings indicate that subsurface drains are useful in monitoring solute movement through the unsaturated zone to the ground water.

MATERIALS AND METHODS

Undisturbed lysimeter construction and installation

A method was developed for the fabrication of large cylindrical lysimeters, 24 in (61 cm) diameter by 60 in (152 cm) long, which would contain undisturbed soil profiles and be instrumented to allow leachate sampling and soil moisture determinations. In order to extract an undisturbed soil core of such size, the United States Bureau of Reclamation (USBR) well drilling crew constructed a large steel cutting bit (Fig. 1). The bit consisted of a 60-in long steel cylinder with a cutting bit on the bottom end. The top end was fitted with an attachment to allow a well drilling pile driver to be connected to it. The diameter of the cylinder was such that a 66-in (168-cm) length of 24-in (61-cm) diameter PVC (poly-vinyl chloride) water pipe would fit inside. The inner lip diameter of the cutting bit was 1/8 in smaller than the inside diameter of the PVC pipe to reduce drag and compaction of the soil core during the coring procedure.

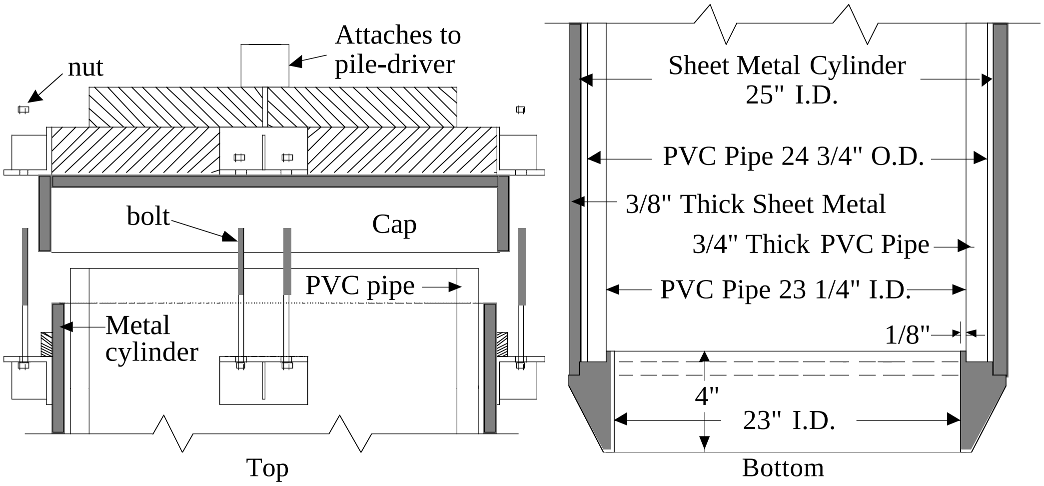

Fig. 1. Drawing of cutting bit used to obtain large undisturbed soil cores.

A 14-in (35-cm) thick layer of top soil was removed with a payloader from the site selected for core extraction and the PVC pipe was loaded into the cutting bit. The cylinder was capped and attached to a well drilling rig pile driver. The pile driver weight was dropped repeatedly on the cutting bit assembly, driving it into the soil a fraction of an inch with each impact of the weight. A back-hoe was used to carefully excavate around the cylinder during the coring procedure to reduce drag on the outside of the bit. The cylinder was continually monitored to assure that it remained perpendicular to the soil surface at all times.

When the cutting bit and PVC pipe reached the desired depth and the pipe was filled with a soil core, the remaining soil was excavated away from the sides of the cutting bit with the back-hoe. A metal plate was forced under the soil core and cutting bit and attached with chains to the cylinder to keep the soil core intact inside the cutting bit cylinder while it was lifted from its hole. A large crane was needed to lift the heavy core (approximately 1 ton) to the surface where it could be removed from the steel cutting bit and instrumented. After the core was removed from the steel cylinder, the void at the top of the core not occupied by the soil core (approximately six inches) was filled with a number of plywood disks and another cap was attached. This allowed the PVC pipe containing the soil core to remain intact while being inverted for instrumentation.

After the core was inverted, approximately 8 in (20 cm) of soil (C horizon material) was removed and placed aside for future use. A dual assembly of 1/2-in (1.27-cm) diameter 1-bar ceramic candles was installed in the bottom of the evolving lysimeter. This leachate extraction system consisted of one primary and one backup system each comprised of four sections of ceramic candle material connected with plastic tubing (Fig. 2). One end of each system was connected to a reservoir to collect the leachate and the other end served as an air inlet. Compression fittings were used to connect the ceramic candles through the wall of the lysimeter. The C horizon material which was previously removed from the bottom of the lysimeter was made into a slurry and a portion of it was used to cover the ceramic candles. The ceramic candles would be under tension and serve as the main leachate collection system whose reservoir would contain approximately 4 gallons of leachate.

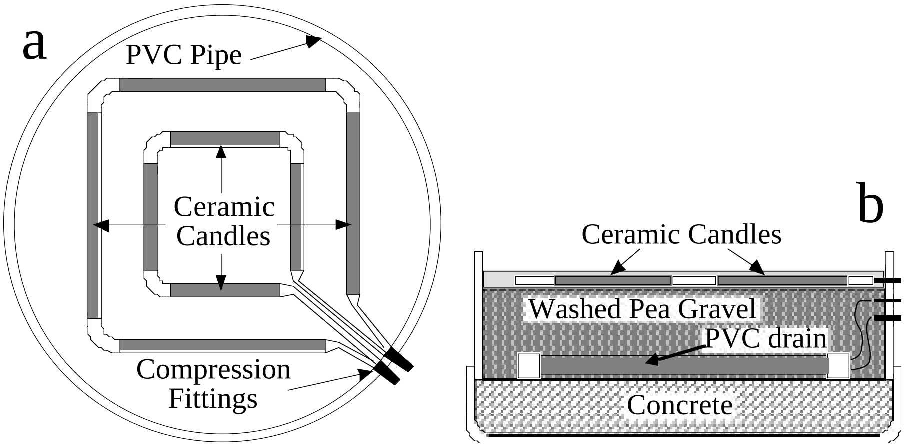

Fig. 2. Leachate extraction system showing a) top view of vacuum extractors and b) side view of vacuum and gravity systems.

Washed pea gravel was placed on top of the C horizon slurry to a depth of approximately 5 1/2 in (14 cm) or flush with the bottom of the lysimeter. Into this gravel was inserted a 21-in (53-cm) length of 1 1/2-in (3.8-cm) #10 slot PVC screen with end caps. As with the ceramic candle system, there were two connections to the slotted PVC; one for leachate removal and one for air intake. The slotted PVC was connected through the wall of the lysimeter with compression fittings. This gravity drain would serve as a back-up leachate collection system in the event the vacuum extractors were unable to recover all the leachate during a large drainage event. Approximately 2 1/2 gallons of drainage may be stored within the pea gravel gravity drainage reservoir.

After the leachate collection systems were installed, the bottom of the lysimeter was capped with a large PVC cap which was previously filled with concrete. Concrete was used to fill the bottom of the cap so that it would be flush with the pea gravel in the bottom of the lysimeter and no settling would occur. The cap was welded to the bottom of the lysimeter with a two-part PVC epoxy to assure a permanent, leak-free seal. The entire system was tested for leaks by applying a vacuum and watching for a drop in tension over a 12-24 h period.

Stainless steel rods were inserted through the sides of the lysimeter to serve as waveguides for soil moisture determinations using time domain reflectometry (TDR) (Topp et al., 1980). The stainless steel rods were 1/8 in (0.32 cm) in diameter and 18 in (46 cm) long. They were inserted in pairs perpendicular to the wall of the lysimeter with 2 in (5 cm) between waveguides. The waveguides were connected to a 300/75-ohm television balun which was connected to coaxial cables. They were installed at 12 in (30 cm) intervals starting at a point that would be 24 in (61 cm) below the soil surface once the lysimeter was in its final position down to 60 in (152 cm) below grade (24, 36, 48, and 60 in, respectively).

All air inlet lines and drainage lines (1/4-in-100 psi polyethylene tubing) from the leachate collection systems as well as the coaxial cables for the TDR system were attached to the side of the lysimeter and enclosed in a half shell of 4 in (10 cm) PVC pipe. A length of 2 in (5 cm) diameter PVC was used to house the drainage lines and cables from the bottom of the lysimeter out to their termination point approximately 30 ft (9 m) away.

As in the coring procedure, approximately 14 in (35 cm) of topsoil was removed from the area where the lysimeter was to be installed (this area was as close as possible to the site from where the core was originally taken). This top soil was set aside to be used to cover the lysimeter after installation. Once the topsoil was removed, a 27-in (67-cm) diameter power pole auger was used to create the hole which would receive the lysimeter. An endless chain trencher was used to dig the trench from the base of the lysimeter to the termination point of the drainage lines and TDR cable which was approximately 30 ft (9 m) away where a pit was dug. A crane was used to lower the lysimeter into the soil and area around the lysimeter was filled with soil and tamped to prevent settling. Approximately 6 in (15 cm) of the top of the PVC pipe not containing soil was sawed off leaving the top of the undisturbed soil core flush with the top of the PVC pipe. At this stage the lysimeter was approximately 14 in (35 cm) below grade and the previously removed topsoil was returned to the top of the lysimeter and surrounding area.

At the termination point of the drainage lines where a pit was previously dug, simultaneous work was being done on the drainage reservoir and vacuum reservoir tank. A capped section of 8-in diameter PVC pipe was constructed to serve as a reservoir for leachate collected from the vacuum extractor system. This 4-gallon capacity reservoir was connected in line with the ceramic candles and a large tank used as a vacuum reservoir. The reservoirs were connected in such a manner that allowed drainage in excess of 4 gallons to overflow into the vacuum tank and no leachate to be lost. After the reservoirs were connected they were covered with soil so that the only evidence of the buried lysimeter was the portion of 2 in pipe housing the lines and cables at the termination point in the access trail.

All lines were brought into an all-weather service box. The drainage and air inlet lines were attached to a brass bar holding stopcocks and a vacuum gauge. Each line was connected to its own stopcock to allow for separate evacuation of the vacuum and drainage reservoirs as well as replenishment of the vacuum in the vacuum reservoir. The coaxial cables were also attached to a common plate in the service box to allow easy connection to a Tektronix 1502B cable tester whenever soil moisture measurements were required.

A schematic view of a typical lysimeter as it is located in the test field is shown in Fig. 3. The top of each lysimeter is located approximately 14 in below grade to allow normal cropping practices to continue and allow for a good representation of leachate quality and quantity under undisturbed field conditions. The drainage and vacuum reservoirs are also completely buried and are located below the service box approximately 30 ft from the lysimeter itself. The service box is located on an access trail transecting the field which allows easy access for leachate sampling and soil moisture measurements throughout the growing season without disturbing the crop.

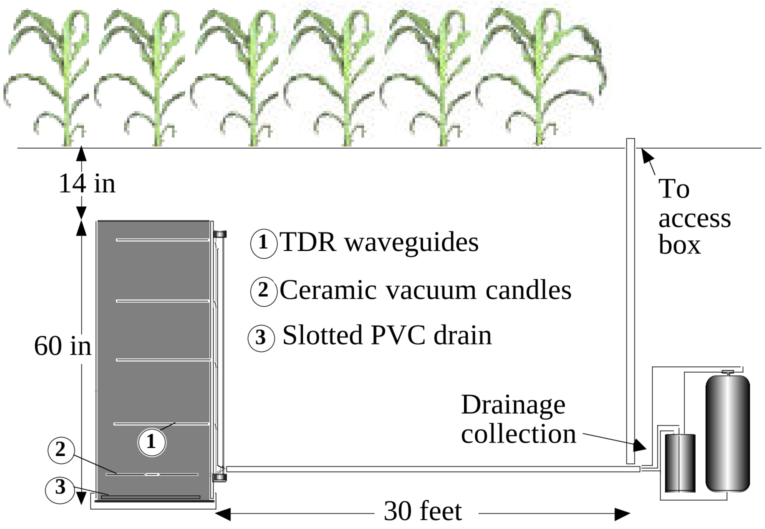

Fig 3. Schematic of the installed undisturbed lysimeter.

<u>Disturbed lysimeter construction and installation</u>

Four large disturbed or reconstructed profile lysimeters were also installed to monitor leachate losses and provide a method for determining water balance. All four lysimeters were filled with a Hecla soil (sandy, mixed Aquic Haploboroll) from a common borrow site to provide a common medium for determining the effect of different water management regimes. Construction of the disturbed lysimeters differed from the undisturbed lysimeters in that the soil contained in the lysimeter was not an intact soil column, but a reconstructed soil profile. The lysimeters consisted of a large steel tank containing soil connected via a drainage pipe to a service manhole.

The lysimeter sides and floor were assembled from 3/16 in (4.76 mm) sheet steel with all seams being welded inside and out. A 2- X 2-in angle iron was welded to form a ring 1 ft from the top on the inside of the 4- X 5-ft cross section by 6 ft deep tank. This was to divert any wall flow away from the lysimeter wall back into the soil column. The floor of the lysimeter was sloped 10% toward a drain outlet. On the down slope side of the floor, a 2-in diameter hole was cut to receive a 1 1/2-in steel coupling for a drain outlet.

The manholes were assembled in a similar fashion. The dimensions of the manhole tanks were 4 X 4 ft in cross section by 9 ft deep. A permanent ladder was affixed to the inside wall of the manhole. A 1 1/2-in steel coupling was welded into a 2-in hole in the side to serve as a drainage inlet. Angle iron was welded around the outside of the manhole tank to prevent collapsing of the tank walls due to soil pressure. Additionally, angle iron was welded around the inside of the tank 12 in off the floor to support a suspended floor made of expanded metal. A hinged lid was attached to the top of the manhole tank for easy access.

After construction of the tanks, they were filled with water and allowed to stand for several hours while all seams were inspected for leaks. If no leaks were detected, the lysimeters and manholes were finished with RUST-OLEUM High Performance Epoxy Paint. The tanks were then transported to Oakes for installation in the BMP field.

A 20- X 40-ft area by 10 ft deep (6 X 12 X 3 m) was excavated to receive each lysimeter and manhole pair. The soil was excavated and stock-piled by layer for later use as back-fill. Envelope gravel was used as a sub-base for a concrete base. Before installation, the bottoms of the tanks were covered with roofing asphalt to protect the epoxy finish during installation. The tanks were then placed on concrete pads and secured with stainless steel anchor bolts and tie-down straps.

In addition to the epoxy paint, two anode treatments were used for corrosion protection. Anode blocks were bolted to the insides of the tanks and anode bags were Cadwelded to the outside of the tanks.

A bed with a 2% slope was prepared between the manhole and lysimeter tanks for the drain pipe. Schedule 40 PVC pipe was connected between the lysimeter outlet and the manhole inlet and leak tested. A piece of 6-in diameter corrugated plastic drain tile was placed around the drain pipe at the manhole and lysimeter. This served to keep the compacted soil away from the connections allowing some movement without excessively stressing the drain pipe connections.

At this point, the area around the two tanks, which was now free standing in the excavated pit, was partially back-filled with the previously excavated soil layers using heavy equipment. The level of each layer being back-filled was periodically checked via transit to verify that representative depths were being achieved.

After back-filling to the top of the lysimeter tank, the lysimeter itself was filled with soil. As noted previously, the soil for all four lysimeters was taken from a common borrow pit area. Plywood boxes, 1 1/2 X 4 ft (0.5 X 1.2 m) square were constructed to hold the soil layers. The boxes were lined with plastic to conserve the moisture in the soil.

A 4 X 5 ft (1.2 X 1.5 m) plywood digging template was used as a guide for excavating each soil layer. This template was placed on the area to be excavated and a back-hoe was used to remove the bulk of the soil around the template. The remaining soil column was hand trimmed so that the template could be pressed down around the soil column to the desired depth. The soil inside the template was shoveled into storage boxes for transport to the disturbed lysimeter site. Transit readings taken at the beginning and end of each lift determined the actual depth of soil removed. Bulk density samples were taken in the borrow pit site to compare to the density of each layer restored in the lysimeter.

Prior to filling the lysimeter with the soil layers, a nylon matting was placed on the lysimeter floor and a stainless steel well screen was installed inside the lysimeter to prevent gravel and soil from entering the drain. Then a layer of pea rock was placed on top of the nylon matting. The actual depth of the pea rock was determined by the difference of the total depth of soil from the borrow pit and the actual depth of the lysimeter floor below the surrounding field surface.

Actual lift increments were marked on the inside of the lysimeters to guide even soil distribution during the filling operation. The lysimeters were filled in 3-in lifts. Each lift was manually tamped to the proper thickness using wood tamping blocks. After tamping to the guide line, the actual thickness was measured using a transit. If the proper thickness was achieved, three bulk density samples were taken to verify that the layer was restored to the bulk density of the original field site.

After all layers had been reconstructed, two permanent access tubes were installed in each lysimeter. The top of each tube was set 14 in (36 cm) below the soil surface and plugged with a rubber stopper. The accurate location of the lysimeter and access tubes was made by triangulation using manhole corners for references. The remaining overburden was then replaced so that the finished lysimeter rested 14 in below grade and approximately 30 ft (9 m) from the manhole tank (Fig. 4).

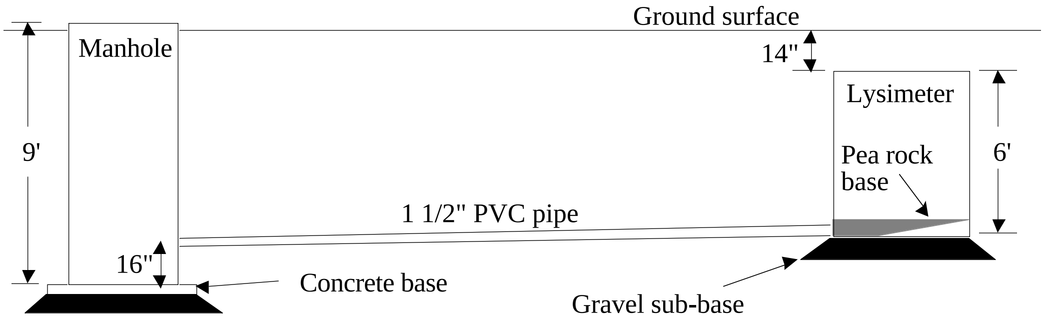

Fig. 4. Schematic of the installed disturbed lysimeter.

This configuration would allow normal farming practices to continue over the top of the lysimeter while allowing easy access to the manhole for routine leachate sample collection. This procedure was repeated in each of the four quadrants of the BMP field, resulting in one disturbed lysimeter under each irrigation treatment.

Sub-surface drain installation

The two subsurface drains underlying the BMP quarter section are part of a complex of drains installed in 1983 and 1984 by the USBR in the Oakes Test Area. Both of the drains are head water drains that start at the southern boundary of the BMP quarter section and flow north.

Installation of the drains consisted of burying a corrugated plastic drain pipe with a Hollandrain chain trencher. A gravel envelope was placed around the drain pipe during the operation to facilitate drainage. The envelope material consisted of graded gravel of which 100% passed through a 1-in screen and 98-100% was retained on a No. 200 screen.

At locations in the field where the drain run changed directions, an access manhole was installed. The manholes consisted of a length of concrete culvert that was installed vertically at the intersection of two drain runs (Fig. 5). Holes near the bottom of the manhole serve as inlets and outlets for the drain pipe. The top of the manhole is covered with a concrete cover used to gain access to the manhole. These manholes serve as access points for routine sample collection as well as periodic drain cleaning. An extra manhole was installed in the east-central portion of the BMP field to allow more accurate drainage measurements from the southeast quadrant of the field. This manhole was constructed of galvanized steel culvert instead of concrete.

Location of all undisturbed lysimeters, disturbed profile lysimeters, subsurface drains, and access manholes is shown in a plan view map of the BMP quarter section in Fig. 5.

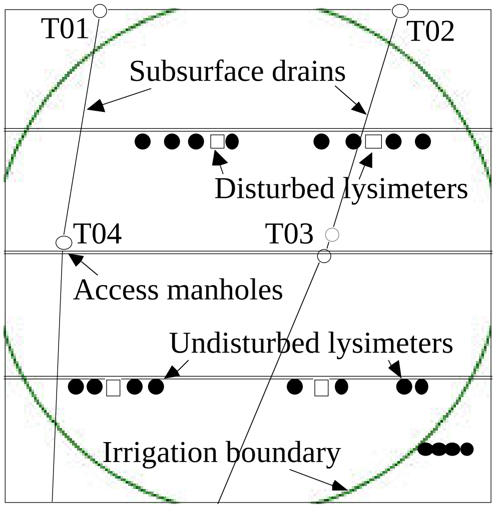

Fig 5. Map of BMP field showing location of lysimetery and subsurface drains.

Sample collection

Undisturbed profile lysimeters were sampled on a weekly basis during the growing season (1 April through 31 October) in 1990 through 1995. During the sampling procedure, total leachate volume was measured and subsamples were taken for chemical analysis. The sampling procedure consisted of attaching a line from a vacuum pump to the stopcock valve for the gravity drain and opening the air inlet stopcock valve. Drainage water would then be collected into bottles attached inline with the vacuum pump. The sampling device was designed as to allow one bottle to be filled while the volume collected in the other bottle was being measured. The sampling device also provided for subsampling for chemical analysis. The gravity drainage reservoir has a maximum capacity of approximately 2.5 gallons. After the gravity drainage ceased, both stopcocks were closed. The extractor portion of the drainage was sampled from the extractor stopcock valves in a similar fashion. After all leachate was collected from the extractor system, a tension of 10 cbar was applied to the ceramic candles for the coming week.

Sample collection from the disturbed lysimeters was initially done with an automated waste water sampler which could be programmed to take drainage samples at a variety of intervals. This method was used for the first years of the study but equipment problems made it necessary to simply place a sample collection bottle under the drain outlet for a few hours to collect the sample. Samples were taken on a weekly basis at the same time as the undisturbed lysimeters. Drainage volumes from the disturbed lysimeters were measured hourly with a tipping bucket rain gauge which was placed under the drain outlet in the manhole. The drainage data was recorded with a Campbell CR-10 datalogger along with other climatic data such as solar radiation, air and soil temperatures, and precipitation.

Water samples from the subsurface drains were taken weekly from each of the four access manholes. A stainless steel bucket was lowered through the manhole to get a grab sample of the drain effluent.

RESULTS AND DISCUSSION

Construction measurements

A concern during the collection of the undisturbed soil cores was the amount of compaction that might occur as the bit was pounded into the soil. Measurements taken after each core was extracted showed that compaction of the 66-in (168-cm) column ranged from 1/8 to 3 1/8 in (0.3 to 7.9 cm). The average reduction in total column length from compaction across all lysimeters was 1 1/2 in or 2.3%.

Bulk density measurements were taken at the common borrow pit and from each layer of each of the reconstructed lysimeters. Bulk density averaged across all lysimeters varied from 0.62 to 4.37 lb ft^{-3} (0.01 to 0.07 g cm^{-3}) from the original soil in the borrow pit for each depth. Bulk density for any given lysimeter and depth varied a maximum of 8.3% while a number of the layers were repacked to exactly the same bulk density as the original soil. The average variation of repacked to original borrow pit bulk density for any soil layer was only 2.9%, indicating good reconstruction of the layers in the lysimeters.

The minimal compaction measured in the undisturbed cores and the good correlation of pre- and post-construction bulk density measurements in the disturbed lysimeters indicate that the soil in each of the two types of lysimeters is physically representative of the BMP field.

Root zone water quality

Lysimeter leachate nitrate concentrations are the first indication of the amount of nitrate moving past the crop root zone at the BMP site. Summary data collected from the undisturbed lysimeters are shown in Fig. 6. Included are the average nitrate-N concentrations for the 16 undisturbed lysimeters in the irrigated portion of the field from 1990 through 1995. Two lysimeters (L02 and L04) in the northwest quadrant of the field were left out of the calculations for 1992 through 1995 due to possible leaks which influenced drainage. Initially after installation, leachate nitrate was quite high. This was in part from high residual soil nitrate as the corn crop was removed prior to maturity for construction. Another contributing factor was the increase in mineralized nitrogen from initiation of irrigation at the site. The yearly average nitrate concentration was 124 in 1990, 68 in 1991, 24 in 1992, 11 in 1993, 13 in 1994, and 8 mg L^{-1} in 1995. The slight increase in leachate nitrate-N in 1994 was due to a high fertilizer-N application rate in 1993 of 135 lb/acre (151 kg ha^{-1}) and poor crop utilization from lower than normal crop production. The standard deviations for nitrate concentration were 77 for 1990, 63 for 1991, 24 for 1992, 9 for 1993, 8 for 1994, and 5 mg L^{-1} for 1995. The relatively high standard deviations indicate the inherent variability of the soil contained in the undisturbed lysimeters. It appears that the undisturbed lysimeters have equilibrated to this continuous corn cropping system and that the BMPs incorporated into the study have resulted in very low N losses from the root zone.

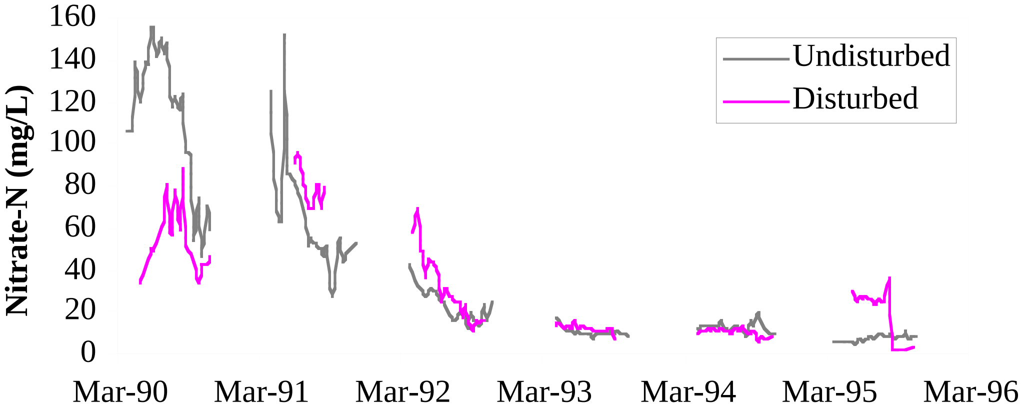

Fig 6. Undisturbed and disturbed lysimeter average leachate nitrate-N concentrations.

The disturbed profile lysimeters show a trend in nitrate concentration similar to that of the undisturbed lysimeters in that the concentrations were initially high and then decreased (Fig. 6). However, in the disturbed lysimeters, the peak came in the second year of operation. The average nitrate concentrations were 55 in 1990, 81 in 1991, 31 in 1992, 13 in 1993, 11 in 1994, and 23 mg L^{-1} in 1995 (4 mg L^{-1} in 1995 if LSW data disregarded). We believe that the lag in the nitrate peak as compared to the undisturbed lysimeters was due to the additional time required for the reconstructed soil to equilibrate. Standard deviations of 37, 22, 21, 6, 5, and 3 mg L^{-1} for 1990 through 1995, respectively, indicate that the variability is not as great as was seen in the undisturbed lysimeter nitrate concentrations. This is a result of the soil in each lysimeter coming from a common borrow area. The peak in nitrate measured in 1995 was due to a fertilizer spill on lysimeter LSW in 1994. We calculated that the amount of N applied to LSW at V6 was 203 lb/acre (228 kg ha^{-1}) instead of the recommended rate of 65 lb/acre (73 kg ha^{-1}). This impromptu tracer experiment indicates that about 1 y is required for surface applied chemicals to move to a depth of 6 ft at this site.

A comparison can be made of the two lysimeter methodologies with regard to nitrate-N concentration. Yearly average nitrate-N concentrations correspond very well between methods with the exception of 1990. The Pearson correlation coefficient (r) for disturbed versus undisturbed nitrate-N is 0.99 for 1991 through 1995 and 0.77 for 1990 through 1995.

<u>Lysimeter drainage</u>

Leachate volumes for the irrigated undisturbed lysimeters and disturbed profile lysimeters are compared in Fig. 7. Differences between the undisturbed drainage and that measured with the disturbed lysimeters is due in part to equipment failures resulting in loss of drainage data. Also, the undisturbed lysimeters may have collected more drainage through the vacuum extractor system versus the free gravity drainage system of the disturbed lysimeters. This is most certainly the case in 1990. In 1990, the tension applied to the ceramic candle system of the undisturbed lysimeters was 30 cbar compared to 10 cbar for 1991 through 1995. Initially, 30 cbar was thought to be a good estimation of the field capacity tension of the C horizon material. After the first year of operation and completion of moisture release work, it was concluded that 10 cbar would more closely match the field capacity tension. Pearson correlation coefficient (r) for disturbed versus undisturbed lysimeter drainage for 1990 through 1995 was 0.71.

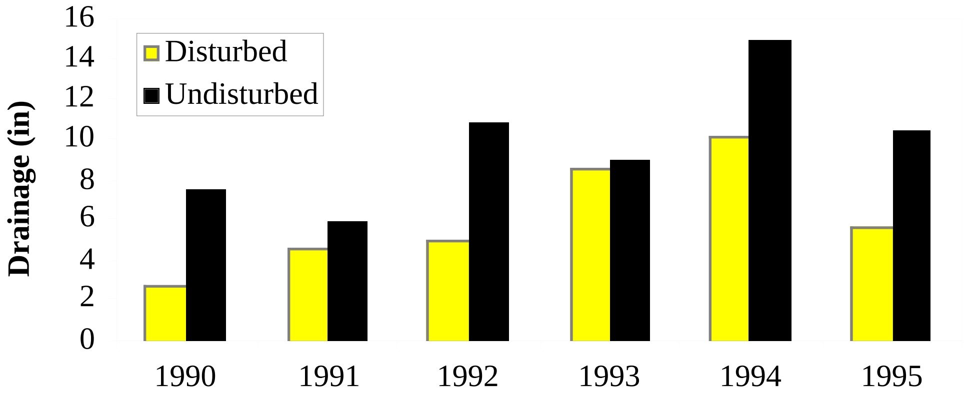

Fig. 7. Disturbed and undisturbed yearly lysimeter drainage.

Water balance data for the undisturbed lysimeters for 1994 is presented in Fig. 8. This data shows that the drainage amounts collected from the lysimeters is reasonable because the water added to the system; spring soil profile water and precipitation, is approximately equal to water removed from the system; fall soil

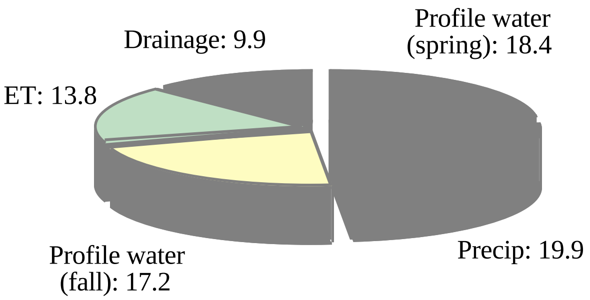

Figure 8. Average water balance for undisturbed lysimeters for 1994.

profile water, drainage, and evapotranspiration. The amount of drainage shown in Fig. 8 differs slightly from that shown in Fig. 7 because some drainage occurred both before and after the dates when the soil profile water measurements were taken.

Irrigated versus dryland

A comparison can also be made between the undisturbed lysimeters in the irrigated portion of the field and those in the dryland portion of the BMP quarter. Figure 9 shows the yearly average nitrate concentrations for the 16 irrigated and 4 dryland undisturbed lysimeters. Concentrations follow the same decreasing trend, however, the dryland lysimeters show a higher concentration in all years but 1990. This is most likely due to lower drainage amounts from the dryland area. Drainage amounts from the dryland lysimeters follow the same trend as the irrigated drainage (Fig. 9). However, the irrigated drainage averages 4.6 in more than the drainage under dryland conditions.

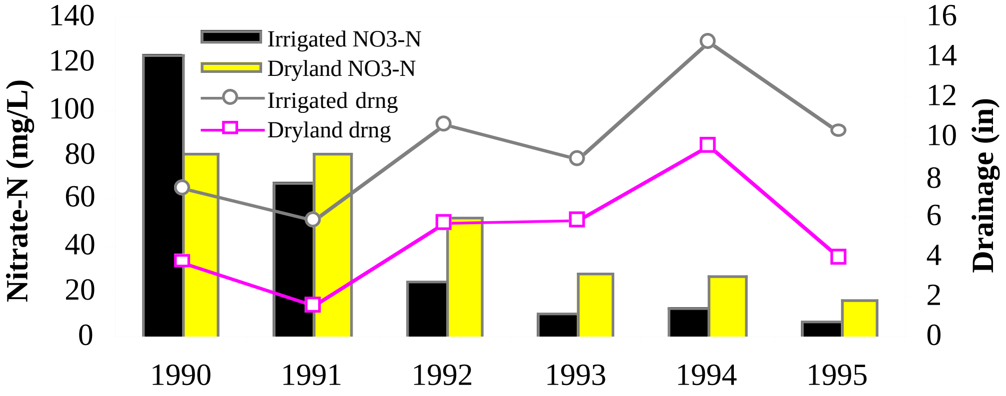

Figure 9. Irrigated and dryland yearly average nitrate-N and drainage.

The two lysimeter methods have performed very well throughout the project with a few exceptions. Two of the undisturbed lysimeters have apparently developed leaks which resulted in ground water entering the gravity drainage collection system when the water table is high. Also, rodents have caused problems with two other undisturbed lysimeters by chewing through the exposed vacuum lines connecting the ceramic candles to the drainage collection container. The only problem with the disturbed lysimeters has been leakage of spring snowmelt into two of the lysimeter manholes. Barring problems of this nature, the lysimeters should perform satisfactorily for many years.

Ground water quality

Subsurface drains under the BMP quarter section have shown a slight increase in nitrate concentration between 1990 and 1993 (Fig. 10). The average nitrate measured at the four access manholes was 3.3 in 1990, 4.9 in 1991, 5.0 in 1992, 5.2 in 1993, and 5.2 mg L^{-1} in 1994. However, in 1995, the average dropped to 4.6 mg/L. This trend shows that the ground water influenced by the subsurface drains lags three to four years behind the lysimeter root zone nitrate.

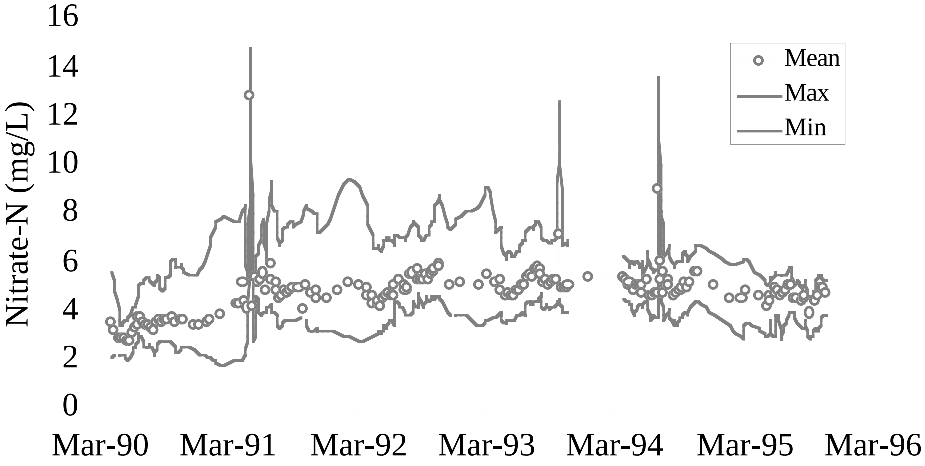

Fig. 10. Subsurface drain nitrate-N concentrations.

The low concentrations of nitrate found in the drain effluent are resultant from N reduction and immobilization caused by iron bacteria lining the inside of the drain lines and is discussed in more detail by Knighton et al., (1997).

A number of sharp nitrate spikes were observed throughout the study. The spike measured on 8 May 1991 was in response to 3 1/2 in (8.9 cm) of rain that fell on 1 May and 6 May 1991. The nitrate spike on 8 July 1994 was in response to 5 in rain on 5 July and 8 July 1994. This spike was also after fertilizer application of 135 lb N/acre (151 kg ha^{-1}) on 28 June 1994.

The rapid response of the subsurface drains to large recharge events resulted in a tracer study to investigate depression-focused recharge (Derby, 1997). The tracer study involved spreading potassium chloride on the soil surface and monitoring the chloride movement through the vadose zone and into the ground water. We found that, in small topographic lows, chloride moved rapidly to the ground water and into subsurface drains after spring thaw or heavy rains. This suggests that the nitrate spikes were not anomalies and were caused by infiltration of ponded water in topographic depressions moving nitrate preferentially to the ground water.

By using drain flow and effluent concentration data, and knowing the approximate area drained by each subsurface drain, we can calculate the mass of nitrate-N that left the BMP quarter each year as well as the amount of water in acre-ft. The mass of N leaving the field was 546 in 1990, 1159 in 1991, 1045 in 1992, 949 in 1993, and 1511 lb in 1994. The amount of water leaving the quarter section was 60 in 1990, 67 in 1991, 65 in 1992, 67 in 1993, and 106 acre-ft in 1994. No values are reported for 1995 due to equipment failure in one of the drains.

CONCLUSIONS

The undisturbed and disturbed profile lysimeters at the BMP quarter have proven to be valuable technology in measuring leachate losses from the crop root zone. The methodology developed to construct the undisturbed lysimeters produced instruments capable of accurate collection of root zone water and chemical data. The undisturbed lysimeters compared favorably to the disturbed lysimeters in leachate quality and quantity measurements. The subsurface drains at the BMP quarter have shown quite stable and low nitrate concentrations but have been very responsive to large recharge events from depression-focusing of infiltration and spatially variable ground water recharge.

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