Construction and Performance of Large Soil Core Lysimeters

Nathan E. Derby,* Raymond E. Knighton, and Bruce R. Montgomery

ABSTRACT

A method was developed to obtain large undisturbed soil cores and instrument those cores to collect vadose zone leachate data under agricultural field conditions. Twenty undisturbed soil core lysimeters were constructed at an irrigated-field site in southeastern North Dakota. Construction of the undisturbed lysimeters consisted of utilizing a steel cutting bit to collect large (0.61-m diam. by 1.68-m deep) soil cores in sections of polyvinyl chloride (PVC) pipe, installing a leachate collection system, installing time domain reflectometry (TDR) soil moisture probes, and then finally placing them below grade so normal farming practices could continue. The described method of core collection is an improvement over other methods in that the cutting bit is reusable, the resulting core is larger and deeper than other methods, no heavy static weights are required, and it is not necessary to expose a free-standing soil column. Leachate quality and quantity data is reported for 1990 through 1995 and compared favorably with larger, reconstructed profile lysimeters on the same site. Overall, the lysimeters functioned as intended for the first 6 yr of operation; however, two developed leaks and rodents damaged another. Possible sidewall flow was observed and may be avoidable in future designs.

The use of lysimeters is a proven method for measuring movement of water and chemicals through the soil profile. A number of methods for obtaining undisturbed soil monoliths for lysimeters have been used. One method involves excavating around a column of soil and encasing it in a steel or plywood box (Bowman et al., 1994; Brown et al., 1974; Strock and Cassel, 2001). This method works well in heavy soils where a freestanding soil column can be maintained but not in coarse-textured soils where an exposed soil column cannot support itself. Similarly, other researchers have pressed steel cylinders over an exposed soil column (Brown et al., 1985; Meshkat et al., 1999). The majority of these methods yield cores that are too small in either area or depth to fully encompass the root zone of several actively growing corn (*Zea mays* L.) plants. Another method involves using a static load to force steel cylinders or tanks into the soil (Tackett et al., 1965; Moyer et al., 1996; Schneider et al., 1996). This method requires heavy duty crane equipment and very heavy steel weights or water tanks that could pose a safety hazard.

A leachate collection system must also be installed in the lysimeters after the soil core is obtained. The simplest method for collecting leachate is to simply attach a drainpipe 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. This may cause an unrealistic soil moisture regime and may effect crop growth.

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 utilizing ceramic cylinders 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. More recently, Strock and Cassel (2001) and Bejat et al. (2000) used a grid lysimeter plate under constant tension to collect leachate from specific areas at the bottom of a soil block, which is impractical in a field setting. Brye et al. (1999) used soil matric potential sensors to maintain equilibrium between lysimeter suction and soil matric potential.

Our objectives were to: (i) develop a method to repeatedly collect undisturbed, coarse-textured soil cores large enough to accommodate the rooting area of several corn plants while reducing compaction, minimizing cost, and increasing safety; and (ii) instrument the cores with tension leachate collection and soil moisture measurement systems and evaluate the functionality of the lysimeters to quantify leachate losses in a farm field environment.

MATERIALS AND METHODS

Site Description

Figure 1 shows the lysimeter locations and soil type within the 65-ha field. Eight lysimeters are located along each of two access trails through the irrigated portion of the field and four lysimeters are located in the southeast dryland corner. The site is dominated by Hecla loamy fine sand soil (sandy, mixed, frigid Oxyaquic Hapludoll) on the south half and Wyndmere fine sandy loam soil (coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll), and Stirum fine sandy loam soil (Coarse-loamy, mixed, superactive, frigid Typic Natraquolls) on the north half. Soil texture, bulk density, and soil water characteristic data are presented in Table 1. Samples for bulk density and moisture release data were taken directly adjacent to the location of each lysimeter. Topography of the site is gently rolling 0 to 3% slopes with the lowest elevation in the northwest corner (395.6 m above sea level) and highest in the southeast portion of the field (398 m above sea level).

Lysimeters were placed in groups of four in each quadrant of the field to provide four replications in four irrigation scheduling method treatments that were part of a larger project investigating best management practices for irrigation and fertilizer use (Steele et al., 2000). The site was not irrigated prior to 1989 and was planted to corn in 1989 to 1995. The exact centers of each lysimeter were located by triangulation

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Abbreviations: EXT, extractor system only; PVC, polyvinyl chloride; REC, reconstructed lysimeter drainage; TDR, time domain reflectometry; TOT, total of extractor plus gravity drainage.

from fixed markers so that the farmer could plant a row directly over the lysimeters. The stand was thinned over each lysimeter so that three corn plants were present within each 0.61-m diam.

In addition to the 20 undisturbed soil core lysimeters installed at the site, four reconstructed lysimeters (one in each quadrant) were also installed during the same time period. Construction of these disturbed profile lysimeters involved filling 1.2 by 1.5 by 1.5 m deep metal tanks layer-by-layer with soil from an adjacent area in the field. Leachate was collected via a slotted PVC gravity drain system in a gravel layer in the bottom of each tank. The tops of the tanks were located below grade at the same depth as the undisturbed lysimeters. Data from 14 of the undisturbed soil core lysimeters in the irrigated portion of the field is compared with data from the larger, more traditional reconstructed profile lysimeters.

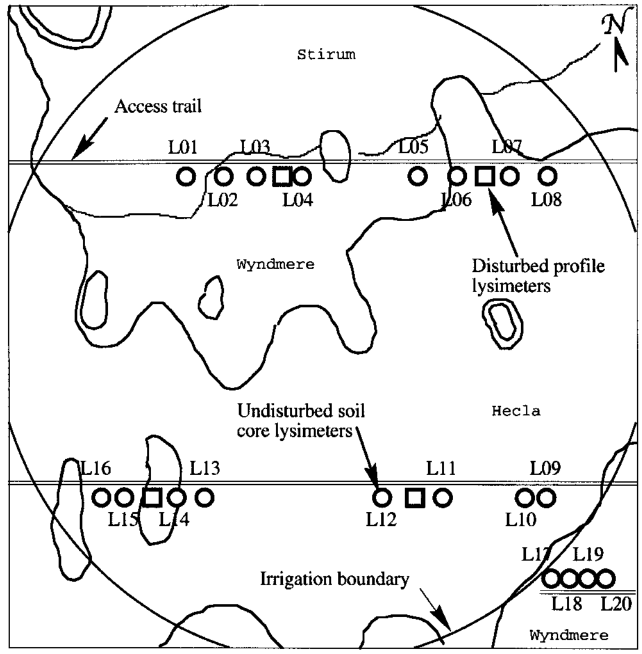

Fig. 1. Plan view of the 65-ha field showing lysimeter installation locations (circles) and soil type.

Soil Core Collection

Large PVC pipes, 0.59-m i.d. by 1.68 m long, were used in the construction of undisturbed soil core lysimeters (Fig. 2). The United States Bureau of Reclamation (USBR) geology crew constructed a large steel cutting bit (Fig. 3) to collect the cores. The cutting bit cylinder was rolled from 9.5-mm sheet metal. The cutting edge was machined and welded to the cylinder. The cost of the cutting bit assembly was approximately \$2000.00 and required heavy machining and manufacturing equipment.

Setup for core collection involved loading a length of PVC pipe into the cutting bit (Fig. 4a) and attaching a driving head that would connect to a pile driver. A 35-cm thick layer of topsoil was removed from the extraction site prior to coring since the completed lysimeter would be placed below grade. The starting elevation of the top of the core was measured. A pile driver was used to drive the cutting bit and enclosed PVC pipe into the soil (Fig. 4b). The 150-kg pile driver drop weight caused the core collection assembly to be driven into the soil approximately 0.5 cm per drop. To reduce compaction and friction during the coring procedure, the inner diameter of the cutting bit was 6 mm smaller than the inside diameter of the PVC pipe. Also, the soil was excavated away from the sides of the cutting bit cylinder with a backhoe as the assembly was incrementally tapped into the soil. When the coring assembly had been hammered down to the final depth, the driving head was removed and a final grade or elevation reading was taken and compared with that of the original soil surface. The difference was the amount of compaction or settling that occurred during the hammering procedure. Once the core was obtained, a metal plate was forced under the soil core (Fig. 4c) and attached with chains. This was done by securing the bottom of the coring assembly to a tractor and then pulling the plate under it with a tractor from the opposite direction. A crane was used to lift the whole assembly (approximately 900 kg) to the surface where the 15-cm void at the top of the core not occupied by soil was filled with plywood disks and another cap was attached. This allowed the soil core to remain intact and undamaged while being inverted for installation of the drainage collection devices. The time required for setup, driving the core into the soil, and cylinder excavation was approximately 6 h.

Lysimeter Instrumentation

Each lysimeter was instrumented to allow leachate sampling at the bottom of the core and soil moisture determinations with depth. To install the drainage col-

Table 1. Mean bulk density and moisture release data with depth from samples taken immediately adjacent to undisturbed soil core extraction areas (UND) and from reconstructed lysimeters (REC)†.

Location	Depth	Texture Range‡	Bulk Density	Water Content at Specified Pressures 0.01 MPa	0.03 MPa	1.5 MPa
	cm		Mg m^{-3}	m^3 m^{-3}		
UND	0–30	lfs-l	1.43 (0.07)§	0.27 (0.07)	0.17 (0.05)	0.09 (0.02)
UND	30–61	lfs-l	1.39 (0.07)	0.29 (0.07)	0.18 (0.05)	0.10 (0.03)
UND	61–91	lfs-l	1.40 (0.06)	0.26 (0.07)	0.16 (0.04)	0.09 (0.02)
UND	91–122	lfs-l	1.40 (0.07)	0.25 (0.06)	0.16 (0.04)	0.08 (0.02)
UND	122–152	fs-scl	1.42 (0.05)	0.26 (0.10)	0.17 (0.08)	0.08 (0.04)
UND	152–183	fs-lfs	1.44 (0.07)	0.25 (0.11)	0.16 (0.08)	0.08 (0.03)
REC	0–30	lfs	1.38 (0.06)	0.27 (0.03)	0.18 (0.02)	0.09 (0.01)
REC	30–61	lfs	1.38 (0.03)	0.28 (0.05)	0.18 (0.03)	0.09 (0.01)
REC	61–91	lfs	1.44 (0.04)	0.29 (0.05)	0.18 (0.03)	0.09 (0.01)
REC	91–122	lfs	1.45 (0.05)	0.23 (0.04)	0.15 (0.01)	0.08 (0.00)
REC	122–152	lfs	1.46 (0.02)	0.22 (0.05)	0.14 (0.03)	0.07 (0.01)
REC	152–183	lfs	1.49 (0.04)	0.23 (0.13)	0.14 (0.08)	0.07 (0.03)

† Values are means from the 20 undisturbed soil core locations and four reconstructed lysimeter sites.
‡ lfs, loamy fine sand; l, loam; fs, fine sand; scl, sandy clay loam.
§ Values in parenthesis are standard deviations.

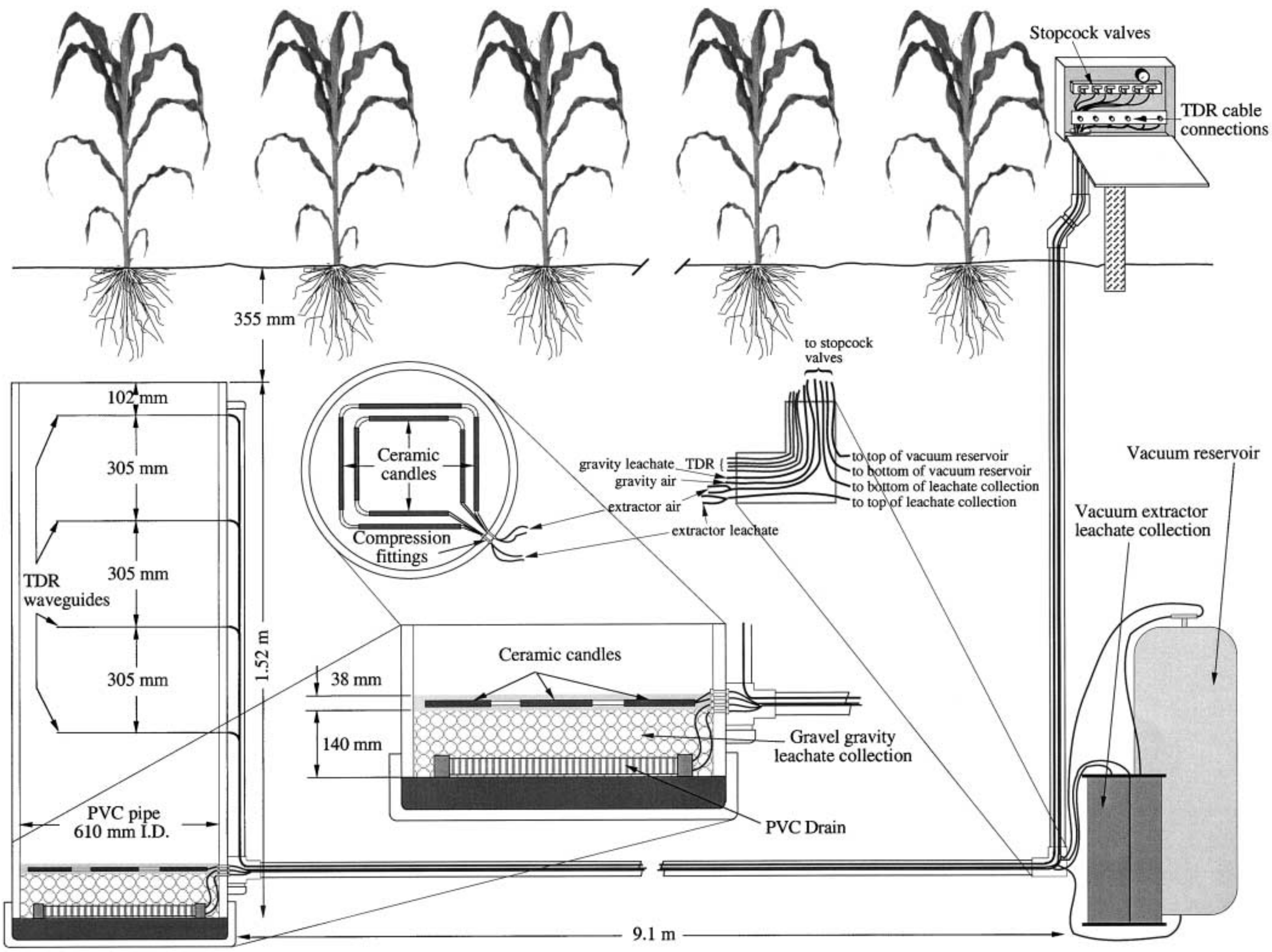

Fig. 2. Schematic of a completed lysimeter in the field showing the instrumentation consisting of time domain reflectometry (TDR) waveguides, ceramic candle vacuum extraction system, and gravity drainage system. Expanded sections shows detail of drainage collection systems and routing of leachate collection tubing.

lection devices at the bottom of the lysimeter, approximately 0.2 m of C horizon material (predominantly fine sand) was removed with a hand trowel and placed aside for future use. Two ceramic cylinder (12.7-mm diam., 0.1 MPa, Soilmoisture Equipment Corp., Santa Barbara, CA, part no. 0640X05-B01M1) vacuum extraction assemblies, a primary and a backup, were installed in the bottom of each lysimeter (Fig. 2 and 4d), and served as the main leachate collection devices. Ceramic cylinders were used because previous experience led us to believe that it would be easier to maintain a leakfree system versus ceramic plates. One end of each ceramic cylinder assembly was connected to a 15-L (51 mm of drainage) reservoir to collect the leachate. The other end was connected to a valve that could be opened during leachate collection to allow air to enter as water was removed. Compression fittings were used to connect the ceramic cylinders through holes drilled in the wall of each lysimeter. A portion of the C horizon material that had been removed was made into a slurry and poured over the ceramic cylinders to ensure good soil-ceramic contact. As this material was primarily loamy fine sand and fine sand (Table 1), making a slurry would not significantly alter the hydraulic properties of the material. The ceramic cylinder extractor system was tested for leaks by wetting the ceramics and applying a 0.05-MPa vacuum. The system was attached to a mercury manometer and if there was a drop in vacuum over a 12-h period, leaks were repaired. Washed pea gravel (approximately 6–12 mm diam.) was then placed on top of the C horizon slurry to a depth of 0.14 m, or flush with the bottom of the PVC pipe. Into this gravel was inserted a capped 0.53-m length of 38-mm, #10 slot PVC screen with two connections; one for leachate removal and one for air intake during sampling. The slotted PVC was also connected through the wall of the lysimeter with compression fittings. The gravel filled portion encompasses the entire diameter of the lysimeter and holds approximately 9.5 L (33 mm drainage). It would serve as a back-up leachate collection system if the vacuum system was unable to recover all the leachate during a large drainage event or if we could not service the system for an extended period of time. Although the textural boundary between the fine sand and the gravel layers would restrict flow until the air-entry value was overcome, this was not perceived as a problem since the

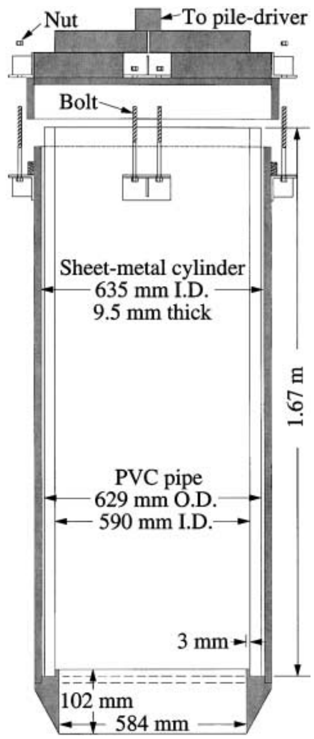

Fig. 3. Schematic of the steel cutting bit used to obtain the large undisturbed soil cores.

gravity drainage system was designed to function as a backup, not the primary source of leachate collection.

After the leachate collection systems were installed, the bottom of each lysimeter was capped with a large PVC cap, the bottom of which was filled with concrete to remove any void space at the bottom of the lysimeter. The slotted PVC gravity drain was now in contact with the concrete. The cap was sealed to the bottom of the lysimeter with PVC epoxy.

Two-probe stainless steel TDR waveguides (3.2-mm diam. by 0.46 m long) were installed horizontally to measure volumetric water content (Topp et al., 1980). Two 3.2-mm holes were drilled in the PVC pipe wall at each TDR location. A device was temporarily attached to the outside of the lysimeter that would assist in aligning the waveguides as they were pushed through the PVC wall and into the soil core. The waveguides were soldered to 300/75 ohm television baluns that were connected to coaxial cables. Waveguides were arbitrarily installed at 0.46, 0.76, 1.07, and 1.37 m below the soil surface. Calibration of the waveguides for this soil was conducted earlier in the laboratory.

All lines (6.3-mm polyethylene tubing) from the leachate collection systems as well as the coaxial cables for the TDR system were enclosed in a half shell of 102-mm diam. PVC pipe attached to the side of the lysimeter. The lines and cables would extended underground 9 m away from the lysimeter in 51-mm diam. PVC so that normal farming practices could continue over the lysimeters while allowing sampling access and reducing the potential for damage near the lysimeter.

Lysimeter Installation

Each lysimeter was installed in a nondisturbed environment as close as possible to the site from where its core was originally taken. It was common to disturb a 10- to 15-m diam. during core collection. A 0.35-m layer of topsoil was removed from the installation area and set aside to be used to cover the lysimeter after installation. Then, a 0.67-m diam. auger normally used for the installation of electrical transmission line poles, was used to create the hole that would receive the lysimeter. An endless chain trencher was used to dig a trench from the base of the augered hole to a pit at the termination point of the drainage lines and TDR cables. A crane was used to lower the lysimeter into position (Fig. 4e) and the void around the outside of the lysimeter was filled with soil. Approximately 0.15 m of the top of the PVC pipe not containing soil was sawed off and the previously removed topsoil was returned to the top of the lysimeter and surrounding area. Bulk density measurements were taken at each soil horizon; however, since the 0.35-m depth of returned topsoil was approximately that of a deep tillage operation, re-creation of the exact original bulk density of the topsoil was not attempted.

At the termination point of the leachate collection lines, a capped section of 0.2-m diam. PVC pipe (15 L capacity) was used as a vacuum tight reservoir for leachate collected from the vacuum extractor system (Fig. 4f). This reservoir was connected to a large vacuum tank that served to maintain vacuum even if the 15-L leachate vessel was full of water. It was connected in such a manner that any leachate in excess of 15 L could overflow into the vacuum tank and no leachate would be lost. The reservoir was buried to keep the collected leachate cool in the summer and reduce the risk of freezing in colder months.

The leachate collection lines and TDR cables are accessed through an all-weather service box. The water collection and air inlet lines were attached to a brass bar holding stopcock valves and a vacuum gauge. Each drainage collection line was connected to its own stopcock valve 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 for soil moisture measurements.

Total cost of materials for each lysimeter installation, including leachate collection systems, TDR probes, all-weather services boxes, and all tubing, connectors and fittings was approximately $800. The time required to instrument and replace lysimeter below grade was approximately 8 h.

Leachate Sampling

Application of the partial vacuum for the ceramic cylinder system was done with a portable vacuum pump. Air was withdrawn from the top of the vacuum reservoir tank until the desired tension was achieved. Then all valves were closed and the closed system would maintain the partial vacuum between sample collection dates (7 d) with only slight losses, depending on the leachate volume collected.

The lysimeters were sampled once weekly during the growing season (1 April through 31 October) in 1990 through 1995. The ceramic cylinder extractor system was under tension during this period only. The soil generally froze to a depth of approximately 0.6 m at the site in the winter months, resulting in negligible drainage; however, if drainage did occur, it was collected in the gravity drainage system and measured in the spring of the following year. The sampling procedure consisted of attaching tubing from a vacuum pump to the stopcock valve

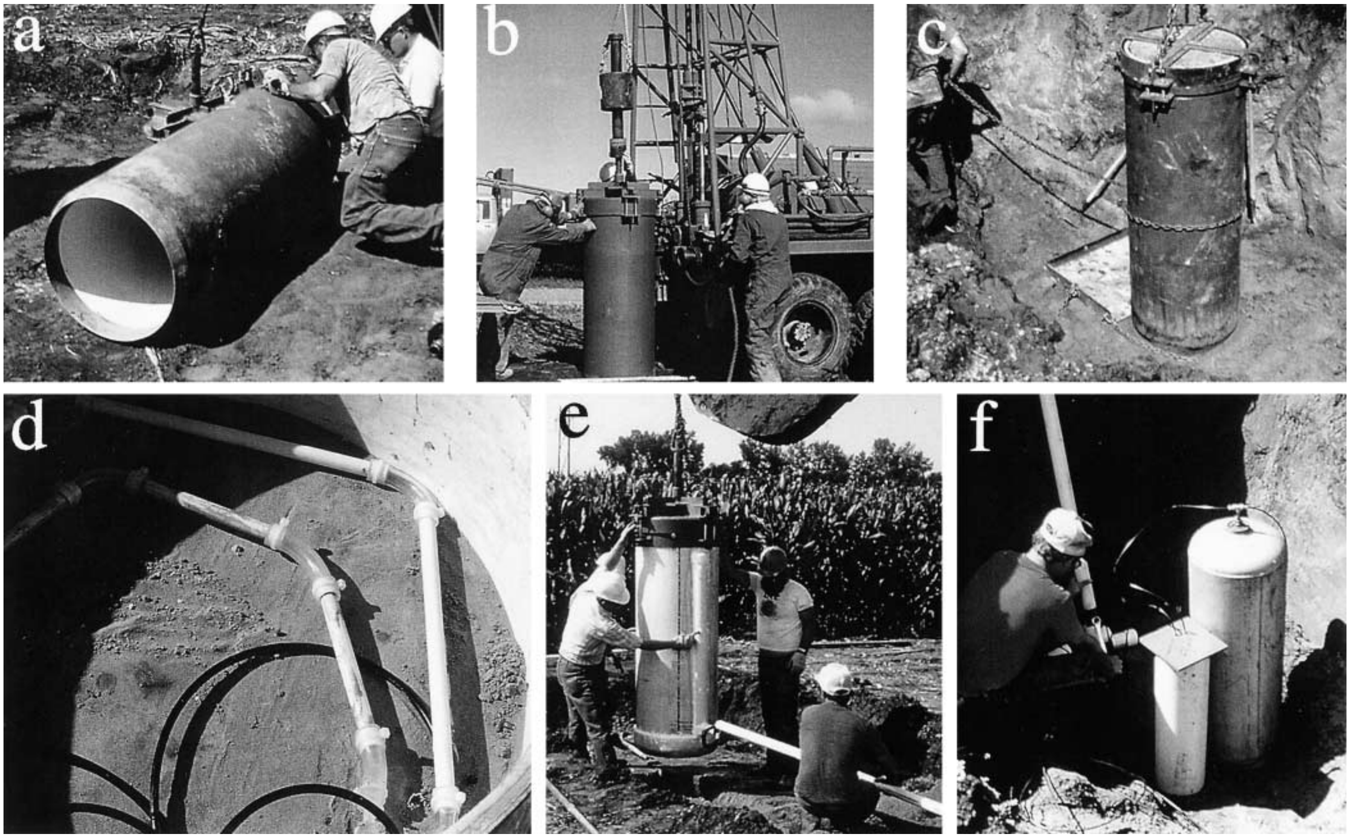

Fig. 4. Core collection and lysimeter installation steps; (a) loading polyvinyl chloride (PVC) pipe into cutting bit; (b) hammering cutting bit into soil to collect core; (c) cutting off soil core; (d) leachate collection system (ceramic cylinder tension extractor); (e) placing the instrumented lysimeter below grade; (f) vacuum extractor leachate collection vessels.

for the ceramic cylinder extractor reservoir and opening that valve and the air inlet stopcock valve. Leachate was collected into bottles attached inline with the vacuum pump and subsampled for NO_3–N analysis. After all extractor drainage was evacuated, a tension of 0.01 MPa (0.03 MPa in 1990) was reapplied to the ceramic candles and all stopcock valves were closed.. The gravity portion of the drainage was collected and sampled from the gravity stopcock valves in a similar fashion. Total volume of leachate was measured with a graduated cylinder and converted to millimeters of drainage, based on the surface area of the lysimeter.

RESULTS AND DISCUSSION

Soil Core Collection

Grade measurements taken before and after each core was extracted showed that compaction or settling of the 1.52-m column ranged from 3 mm in core L04 to 79 mm in core L10. The average reduction in total column length during the core collection procedure across all lysimeters was 38 mm (2.5%) with a standard deviation of 17.6 mm. The settling that occurred may have been the result of the soil core shifting slightly to fill the small void created by the difference in cutting bit versus PVC pipe diameter. No visible fracturing of the soil because of the repeated hammering of the pile driver was observed. Although no measurements were taken from inside the lysimeter core for obvious soil disturbance reasons, we feel that the soil cores in the lysimeters are generally representative of the field.

Leachate Quantity Measurement

Seasonal (1 April to 31 October) drainage amounts from the soil core lysimeters in the irrigated portion of the field are compared with the yearly leachate totals from the disturbed profile lysimeters and applied water (Fig. 5). A distinction is made between leachate collected in the extractor system only (EXT) and the total of extractor plus gravity drainage (TOT). Differences in applied water amounts indicated by maximum and minimum error bars are due to differences in irrigation scheduling methods in each field quadrant (Steele et al., 2000). Essentially no gravity drainage was observed in 1990 due to a higher tension (0.03 MPa) applied to the vacuum extractor systems versus 0.01 MPa in subsequent years. After completion of moisture release work, it was concluded that 0.01 MPa would more closely match the field capacity tension of the C horizon material. Total drainage closely matched reconstructed lysimeter drainage (REC) in 1991 and 1993 while EXT matches REC better than TOT in 1992, 1994, and 1995. Also, in 1990, 1994, and 1995, the maximum measured drainage exceeded the applied water. The variability of this data suggests that preferential flow, perhaps wall flow, may be contributing directly to the gravity drain-

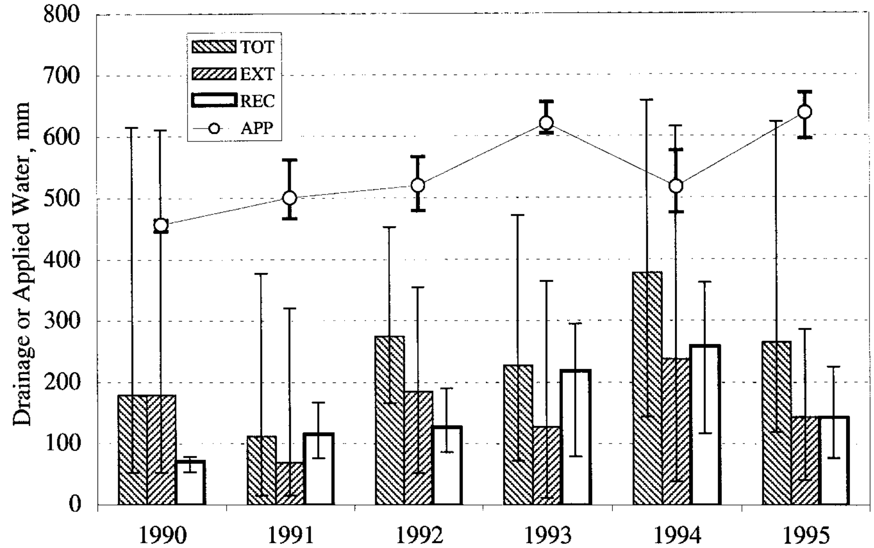

Fig. 5. Total yearly leachate amounts for undisturbed lysimeter extractor system (EXT) and extractor plus gravity (TOT), reconstructed lysimeter drainage (REC) and yearly applied water (APP). Values for undisturbed lysimeters are means of total drainage for 14 lysimeters in the irrigated portion of the field. REC and APP values are means for four lysimeters and rainfall and irrigation totals. Error bars represent the maximum and minimum totals.

age, especially during large rainfall events, in some of the soil core lysimeters. This is substantiated by the findings of Schindler (1996), who attributed rapid ^{15}N movement in these lysimeters to preferential flow.

Leachate Quality Measurement

Leachate NO_3–N from the undisturbed lysimeters is compared with the leachate nitrate from the disturbed lysimeters in Fig. 6. Nitrate concentration was determined by colorimetric, automated Cd reduction (EPA Method 353.2, USEPA, 1983). Nitrate-N concentrations compared favorably for all years except 1990; however, the trends in concentration for the two lysimeter types were similar for all years. High residual soil N because of crop removal for lysimeter construction is the most likely cause of the high leachate nitrate concentrations. The high maximum concentrations shown for the reconstructed lysimeters in 1995 are due to a fertilizer spill over one of the lysimeters.

Soil Water Measurement

The amount of liquid soil water with depth in the lysimeters was measured once weekly via TDR and is summarized with depth for each year (Fig. 7). Water contents at 0.01 MPa from laboratory moisture release measurements are also included. The soil profile in the

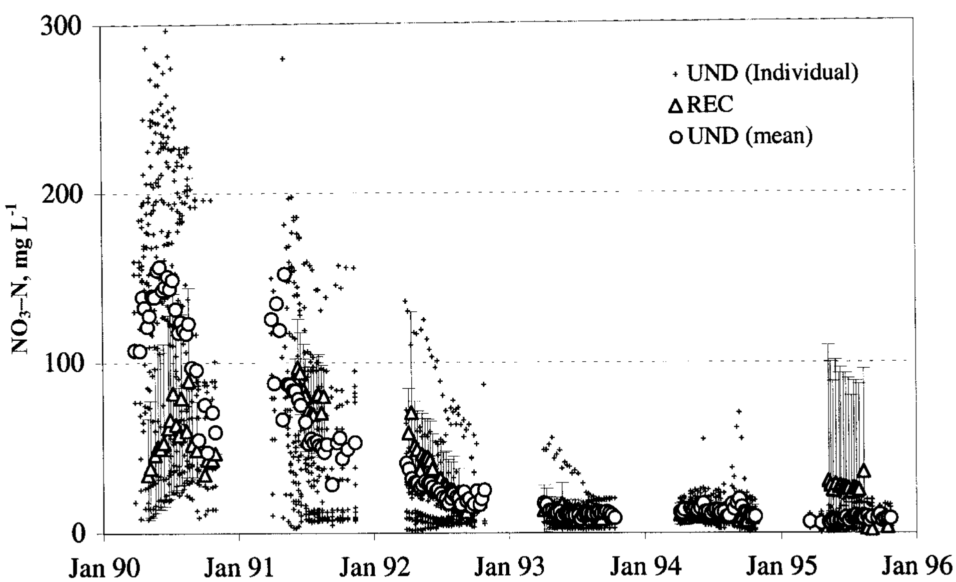

Fig. 6. Average and individual leachate NO_3–N concentrations by week for 14 undisturbed lysimeters in the irrigated portion of the field (UND) and the four reconstructed lysimeters (REC). The error bars are attached to REC and indicate maximum and minimum means by date.

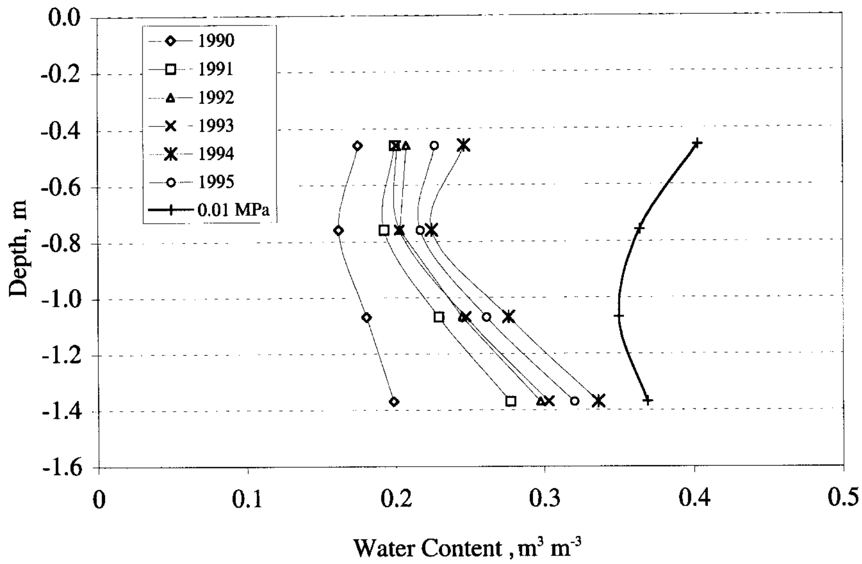

Fig. 7. Average yearly soil water content with depth for undisturbed lysimeters measured with time domian (TDR).

lysimeters was driest in 1990 and wettest in 1994. The trend of increasing soil moisture with time is to some degree an indication of a wetter climatic cycle in the region; however, it may be more a factor of inadequate tension on the vacuum extraction system as water content was also increasing in magnitude with depth.

Coring Bit and Lysimeter Performance

The large cutting bit worked well to collect the large soil monoliths used for the lysimeters. Once the bit was constructed, it was relatively fast, inexpensive, and safe to collect additional cores. The bit showed no signs of damage from repeated coring procedures. We were able to collect deeper cores than would have been possible with other methods that require exposure of a freestanding soil column. The required depth of the soil core was obtained in all instances.

Overall, the leachate collection systems functioned properly during the first 6 yr of operation, yielding leachate quantity and quality information comparable with that measured at the larger reconstructed lysimeters at the site. The vacuum system was capable of holding a relatively constant vacuum for at least 7 d between sampling dates. The gravity drainage system collected excess or off-season leachate missed by the vacuum system. The volume of the leachate collection systems was adequate to contain at least 7 to 14 d of drainage. The TDR probes functioned properly to measure soil moisture content with depth; however, soil moisture probes nearer to the leachate extraction system as well as outside of the lysimeter would have been useful in assessing the performance of the lysimeters.

A number of problems, however, developed with some of the lysimeters. In 1992, lysimeter L02 showed unrealistically high amounts of drainage from the gravity system. Similarly, in 1993, L04 started showing signs of increased drainage from the gravity system. Presumably, a crack had developed somewhere in the PVC or an epoxy seal had broken and groundwater was entering the gravity leachate collection system directly. Water table elevation measurements from adjacent monitoring wells indicated that the water table had risen to a level above the bottom of these lysimeters. The water table was below the level of the bottom of the lysimeter at the time of installation. For this reason, data from L02 and L04 were left out of the drainage and soil moisture calculations presented above.

In 1995, the first evidence of rodent damage was seen at L14 when the vacuum extraction system failed. Pocket gophers (*Geomys bursarius*) cut the plastic lines running from the vacuum reservoir to the leachate collection vessel. Repairs were attempted but it was impossible to keep the gophers from continuing to cut the lines. In future designs the lines for the extractor system which exit the PVC pipe at the point of the leachate collection reservoir (Fig. 2), should be protected. One possibility would be to wrap the exposed plastic lines in stainless steel screen.

The issue of possible preferential flow along the inside walls of the lysimeter should be addressed in future installations. One possible method to reduce wall flow would be to drill holes in the PVC cylinder after core collection and inject expanding polyurethane foam to fill any voids between the soil monolith and the PVC wall as done by Strock and Cassel (2001) and Meshkat et al. (1999).

SUMMARY AND CONCLUSIONS

A method was developed to obtain large undisturbed soil cores and instrument those cores to collect vadose zone leachate data under agricultural field conditions. The use of a large cylindrical cutting bit was successful in obtaining 0.61-m diam. by 1.5-m deep cores in the coarse-textured soil. The core collection method allowed for numerous replications, did not require extremely heavy static weights, and did not require exposure of a freestanding soil column, which would have been impossible at this site. Data collected over the first 6 yr of operation indicate that the leachate quantity and quality were comparable with that measured from larger reconstructed lysimeters on the same site. Possible modifications for future designs include protecting the extractor leachate collection system from rodents, installing additional TDR probes closer to the bottom and outside of the lysimeter, and somehow reducing the potential for wall flow.

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