OPTIMIZATION OF DRAINAGE LYSIMETER DESIGN FOR FIELD DETERMINATION OF NUTRIENT LOADS

APARNA GAZULA[1], ERIC SIMONNE[1]*, MICHAEL D. DUKES[2], GEORGE J. HOCHMUTH[1], ROBERT HOCHMUTH[3] AND DAVID W. STUDSTILL[1]

[1]*University of Florida*
Horticultural Sciences Department
1241 Fifield Hall
Gainesville, FL 32611

[2]*Agricultural and Biological Engineering Department*
107 Frazier Rogers Hall
P.O. Box 110570
Gainesville, FL 32611

[3]*North Florida Research and Education Center—Suwannee Valley*
7580 County Road 136
Live Oak, FL 32060

Additional index words. leachate, nitrogen, phosphorus, best management practice, total maximum daily load

Abstract. **Pollution budgets used in Total Maximum Daily Load allocation requires the determination of nutrient load at the field level. Nutrient load typically is defined as a volume multiplied by concentration of nutrient in sample and can be determined through indirect and direct approaches. Indirect approaches of measuring load such as nutrient flow models and nutrient balances do not allow field-level load calculations. Field measurements may be achieved with resin traps, soil sampling, or leachate lysimeters. Each method requires different calibration equations for field-level calculation of load from actual measurements. Ideally, lysimeters should be wide enough to collect all the water leaching below the root zone, long enough to reflect spatial variability, deep enough to allow for cultural practices above and prevent root intrusion, simple to build, allow for sample retrieval, and be cost-efficient. Existing lysimeter design was improved by increasing the length of collection container, filling the bottom part of the lysimeter with gravel, reducing depth of installation, and/or breaking water tension with a fiberglass wick. Lysimeter cost of fabrication and installation was estimated at $84 for 3.05 m long units. Because nutrient load may occur during or after a crop, lysimeter monitoring and sampling should be done year round.**

Quantifying nutrient load from vegetable production systems is the first step towards monitoring and understanding groundwater pollution in the field. A nutrient load is defined as the mass of a chemical entering or leaving an area, and is calculated as the product of the volume of water that the chemical is transported in and the concentration of the chemical in the water (Rice and Izuno, 2001). Our objectives were to (1) review and compare the methodologies currently used in load determination, (2) detail the actual calculation of the load, and (3) identify a simple design for use in research and demonstration trials on load determinations.

*Corresponding author; e-mail: esimonne@ufl.edu

Techniques for Nutrient Load Determination

Nutrient load can be determined indirectly or directly. The indirect approaches of measuring load include nutrient flow models and nutrient balances. Nutrient flow models are important tools for evaluating the impact of nutrient leaching on water quality at the watershed level, and play an important role in designing agricultural and environmental policies. For example, nutrient models used for determination of N leaching from agricultural land can be classified into statistical regression models, and process-based models, such as ANIMO, SOILN, and DAISY (Kyllmar et al., 2005). Nutrient balances measure the difference between nutrient inputs into and outputs from an agricultural system (Parris, 1998), and can be used as a tool for sustainable nutrient management (Öborn et al., 2003). However, they are only an indirect indication of nutrient losses in the agro-ecosystem (Oenema et al., 2003), and seldom allow the determination of nutrient loads at the field level. Knowledge of nutrient loads at the field level will be needed in the implementation of the Total Maximum Daily Loads legislation (Federal Clean Water Act Section 303 d.).

The direct approaches to calculating load at the field level are resin traps, soil sampling, or leachate lysimeters (Table 1). The essential components of resin traps are the ion exchange resins used to create nutrient filters, and the soil core (usually PVC pipes filled with soil) inside which the resins are buried (such as A400 anion exchange resin or C100 cation exchange resin, Purolite Co., Bala Cynwyd, Pa.; Balkcom et al., 2001). Before starting the monitoring of nutrient leaching, resin traps are buried in the soil below the crop root zone. As water flows through the soil layer and the soil cores containing the resin trap, leached nutrients are intercepted by ion exchange. After resin trap retrieval, nutrients are extracted from the resin and quantified. This method provides nutrient quantity intercepted by the surface of the resin trap which can be extrapolated to field size. Soil sampling is another method for direct load measurement. Typically, a soil sample used for load determination consists of a 1.5 m deep soil core and divided in five subsamples, each 0.3 m long. A known amount of distilled water is added to the sample to saturate it. After thorough mixing of the sample, chemical extraction or analysis can be performed. The chemical concentrations were converted to original field water content basis (Ahmed et al., 2001). Nutrient load may then be calculated provided the volume of soil wetted by irrigation (and where the nutrient concentration is assumed to be homogenous) is known (Dukes et al., 2005).

The third direct technique for load determination is the leachate lysimeter. The two main types of leachate lysimeters are suction cup lysimeters and drainage lysimeters (Abdou and Flury, 2004). Suction cup lysimeters consist of a porous ceramic tip connected to an air-tight buried chamber that is accessible through two sealed tubes. Suction cup lysimeters are installed below crop root zones, usually between the 0.5 and 1.5 m depths. Lysimeter operation generally consists of two steps. First, a soil-water sample is collected by creating a 40 to 50 kPa vacuum inside the chamber with a hand-held pump. Water moves from the soil into the chamber through the po-

Table 1. Advantages and limitations of different methods used for measuring nutrient loads.

	Resin traps	Soil sampling	Suction cup lysimeters	Drainage lysimeters
Advantages	Space bound Small structures Easy to install and simple to build Require minimal labor for sample collection	Not space bound Simple procedure	Space bound Permanent structures Easy to install and simple to build Require minimal labor for sample collection	Space bound Permanent structures Simple to build Require minimal labor for sample collection Give both concentration and volume
Limitations	Underestimate load - capture lower than actual volumes of leachate Space bound Need to be installed every season	Gives only concentration and not volume Require intensive labor for collecting samples Leaves hole in ground	Gives only concentration and not volume Space bound Protracted sampling time Interfere with tillage	Lack universal design Space bound Hard to install Disturb soil profile Might interfere with tillage Require constant maintenance

rous cup because of the difference in pressures. After approx. 24 hrs, samples were retrieved using a vacuum pump (Webster et al., 1993). The leachate collected from these lysimeters was from the soil surrounding the porous ceramic tip, but the exact volume of soil it comes from was unknown. Hence, this technique only gives the concentration of nutrients in solution and cannot be used alone to calculate a nutrient load. Further knowledge of the actual volume of soil the water was collected from needs to be gained. In contrast to suction cup lysimeters, drainage lysimeters collect leachate from macropore flow or when the soil above the lysimeter becomes saturated or exceeds the field capacity (Zhu et al., 2002). These lysimeters consist of two main components: a collection container and a storage container. The collection container is filled with soil, and the storage container is filled with air and holds the leachate caught by the collection container. Drainage lysimeters are installed below crop root zones by digging holes in the ground, thereby disturbing the soil. The storage container is installed below the collection container such that the water collected inside the collection container flows into the storage container by gravity (Migliaccio et al., 2006). The size and shape of both containers may need to be adjusted based on the depth of the crop's root system and soil depth, especially on the calcareous soils of south Miami-Dade County (Migliaccio et al., 2006). Leachate in the storage container is retrieved with a pump. Drainage lysimeters give both concentration and volume of nutrients being leached and thus can be used for load determination at the field level.

Load Calculation

For all techniques that measure both volume and concentration, load may be expressed on a field basis. For crops planted on bare ground, with sprinkler irrigation the conversion factor represents the percentage of surface covered by irrigation. In this case, the load is on a field-surface basis. For mulched crops, with drip irrigation the correction factor represents the fraction of total length of mulch per hectare (and therefore bed spacing) divided by the length of the collection container. In this case, the load is defined as the basis of a length of polyethene mulch per unit surface.

When soil samples are used, the load is calculated by multiplying nutrient concentration in each sub-sample (mg/kg soil) by the wetted soil zone volume (m^3, Width × Length × Depth), by soil bulk density, and by a correction factor for unit homogeneity. The Length is that of mulch and the Depth and Width are those of the wetted zone.

For techniques that measure only concentration of nutrients being leached and not volume (suction cup lysimeters, and some resin traps) nutrient load can also be calculated using the trapezoidal method. The area under a plot of calculated nutrient concentration against estimated drainage is calculated as the sum of the areas of trapezes resulting from successive pairs of sampling occasions (c_1, c_2 $mg \cdot dm^{-3}$), and drainage volume between sampling occasions (v mm). The total N leached in each sampling interval, in $kg \cdot ha^{-1}$ was then given as N leached = $0.5(c_1 + c_2)v/100$ (Lord and Shepherd, 1993).

Optimization of Drainage Lysimeter Design

Design directly affects load determination in two ways because the formula of load calculation involves lysimeter dimensions, and the efficiency of collection affects volume of water collected. Ideally, a drainage lysimeter should have an optimum collection area where the collection container collects leachate from entire root zone below crop root system being tested, and should account for plant-plant and emitter to emitter variability (in case of drip irrigation). The lysimeter should be buried deep enough to not interfere with tillage operations and not to allow for root intrusion. But, the depth should not be too great that it fails to intercept all the vertical water flow below the root zone. Therefore, depth of installation is an important criterion during installation of lysimeters. Also, drainage lysimeters should not cause a perched water table. Instead, they should allow free flow water movement in the collection container, and from the collection container to the storage container.

The development of a permanent or temporary perched water table is likely to affect the volume of water collected and may create favorable conditions for nitrate losses through denitrification (Simonne and Morgan, 2005). Frequency of leachate collection is another factor that may affect load measurement. The leachate collected in the storage container should be retrieved at frequent intervals to prevent changes in the chemical composition of the leachate. If leachate samples are being stored before analysis, the optimum storage conditions are at 4°C without acidification. These conditions minimize N transformations of NO^{2-} and NH^{4+}, and minimize overestimation of NO^{3-} concentrations. Significant increases in ammonium concentrations were seen at 20°C due to mineralization reactions, and significant increases in nitrate concentrations were seen at -20°C and acidic pH due to oxidation of NO^{2-} (Clough et al., 2001).

Leachate collection efficiency may be calculated by dividing total leachate volume collected by total water applied for that time period (Zhu et al., 2002). Factors that may improve collection efficiency are the size of the collection container, and the presence of a wick. Previous work done with large plate lysimeters has shown that collection container sizes of 162, 500 to 2005 cm^2 increased collection efficiencies from 10%, 13%, to 26%-36%, respectively (Radulovitch and Sollins, 1987). In a study comparing zero-tension pan lysimeters and wick lysimeters installed at a depth of 1.3 m below the soil surface, wick lysimeters collected 2.7 times more leachate than drainage lysimeters did, thereby increasing efficiency. The higher efficiency was attributed to the breaking soil water tension by the wick (Zhu et al., 2002).

Proposed Design

Based on these considerations, a prototype lysimeter has been designed: Larger sized collection containers were made with a 9.1 m long, 0.6 m wide piece of polyethylene culvert pipe (corrugated on the outside and smooth on the inside) cut in half installed at the 0.45 m depth and 0.5% slope end-to-end. To break soil-water tension and facilitate free-flow water movement inside the collection container, a 5 cm-diameter schedule 40 PVC pipe cut lengthwise, and riddled with 1 cm diameter holes along the length of the pipe, and with a 6 mm thick and 1 cm long braided fiberglass wicks inserted in one hole per inch was placed on the bottom of each collection container. The collection container was filled with 10-cm thick layer of pea gravel covered with a plastic screen (10^{-6} m^2 pore size) and then with soil. The 213 L capacity storage container was placed immediately under the collection container. A 5-cm diameter PVC pipe (leachate retrieval spout) ran from the bottom of the storage container to 10-cm above soil surface. Flexible polyethylene tubing connected to a peristaltic pump was inserted through the leachate retrieval spout for sample retrieval. The per-unit fabrication and installation cost of this design is estimated at $60 to $84 (based on size of collection container) and requires 6 man-hours. Cost and labor required may be reduced for large quantities of lysimeters.

Literature Cited

Abdou, H. M. and M. Flury. 2004. Simulation of water flow and solute transport in free-drainage lysimeters and field soils with heterogenous structures. Europ. J. Soil Sci. 55:229-241.

Ahmed, M., M. L. Sharma, Q. D. Richards, and M. S. Al-Kalbani. 2001. Sampling soil water in sandy soils: Comparative analysis of some common methods. Commun. Soil Sci. Plant Anal. 32:1677-1686.

Balkcom, K. S., J. F. Adams, D. L. Hartzog, and C. W. Wood. 2001. Mineralization of composted municipal sludge under field conditions. Commun. Soil Sci. Plant Anal. 32:1589-1605.

Clough, T. J., R. J. Stevens, R. J. Laughlin, R. R. Sherlock, and K. C. Cameron. 2001. Transformations of inorganic-N in soil leachate under differing storage conditions. Soil Biol. Biochem. 33:1473-1480.

Dukes, M. D., J. M. Scholberg, and T. A. Hanselman. 2005. Quantification of nitrogen movement under drip irrigated vegetable production. Paper no: 052240, ASAE Ann. Mtg.

Kyllmar, K., K. Martensson, and H. Johnsson. 2005. Model-based coefficient method for calculation of N leaching from agricultural fields applied to small catchments and the effects of leaching reducing measures. J. Hydrol. Amsterdam 304:343-354.

Lord, E. I. and M. A. Shepherd. 1993. Developments in the use of porous ceramic cups for measuring nitrate leaching. J. Soil Sci. 44:435-449.

Migliaccio, K. W., L. Yuncong, H. Trafford, and E. Evans. 2006. A simple lysimeter for soil water sampling in south Florida. Circ. ABE 361, EDIS, http://edis.ifas.ufl.edu/AE387, Univ. of Florida, Gainesville.

Öborn, I. A., C. Edwards, E. Witter, O. Oenema, K. Ivarsson, P. J. A. Withers, S. I. Nilsson, and A. R. Stinzing. 2003. Element balances as a tool for sustainable nutrient management: A critical appraisal of their merits and limitations within an agronomic and environmental context. Europ. J. Agron. 20:211-225.

Oenema, O., H. Kros, and W. de Vries. 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Euro. J. Agron. 20:3-16.

Parris, K. 1998. Agricultural nutrient balances as agri-environmental indicators: An OECD perspective. Environ. Pollution. 102:219-225.

Radulovich, R. and P. Sollins. 1987. Improved performance of zero-tension lysimeters. Soil Sci. Soc. Amer. J. 51:1386-1388.

Rice, R. W. and F. T. Izuno. 2001. Calculating nutrient loads. Res. Tech. Bul. 906, http://edis.ifas.ufl.edu/AE149, Univ. of Florida, Gainesville.

Simonne, E. and B. Morgan. 2005. Denitrification in seepage irrigated vegetable fields in South Florida, Circ. HS1004, http://edis.ifas.ufl.edu/HS248, Univ. of Florida, Gainesville.

Webster, C. P., M. A. Shepherd, K. W. T. Goulding, and E. Lord. 1993. Comparisons of methods for measuring the leaching of mineral nitrogen from arable land. J. Soil Sci. 44:49-62.

Zhu, Y., R. H. Fox, and J. D. Toth. 2002. Leachate collection efficiency of zero-tension pam and passive capillary fiberglass wick lysimeters. Soil Sci. Soc. Amer. J. 66: 37-43.