

**Surface and Subsurface Transport of Phosphorus from Surface and Subsurface-applied
Poultry Litter**

by

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Abstract

A plot scale experiment was conducted in a pasture at the Sand Mountain region of north Alabama, USA. Nine plots of 1.52 m by 3.05 m were constructed with sheet metal borders to isolate runoff. The soil was a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults) and the slope of the plots was 4%. A metal trough attached to 10 cm horizontal approach sheet metal was installed at the downslope end of the plot to collect surface runoff and convey it to a collection point at the corner of the plot. To collect leachate a pair of pan and wick lysimeter was installed 50 cm beneath the soil surface in each plot. There were three replications of each surface-applied, subsurface-banded litter plots, and three control (no litter) plots. For plots with surface application of litter, broiler litter was broadcast manually over the entire plot as uniformly as possible. For subsurface application of litter, subsurface band a applicator was used. Rainfall simulation was conducted at an intensity of 70 mm h⁻¹ based on the 1 h, 10 year return period of that area. Runoff samples were collected every 5 minutes for 1 h after the start of runoff. Leachate samples were collected at the end of the rainfall event. Results showed that irrespective of treatment only 10% of the rainfall contributed to surface runoff. The method of litter application plays an important role in the concentration and loading of nutrients in surface runoff and leachate. Significantly ($\alpha = 0.05$) greater concentration and loading of the nutrients (TP, PO₄-P, NH₄-N, and NO₃-N) in runoff were observed from surface-applied litter plots than subsurface-banded. There was more than 80% reduction in concentration of TP and PO₄-P in surface runoff when broiler litter was

subsurface-banded in comparison with surface-applied litter plots. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations were reduced by about 80 and 74%, respectively, in surface runoff from subsurface-banded litter plots in comparison with surface-applied plots. Similar trends in concentration were seen in the loading of nutrients in surface runoff when broiler litter was subsurface-banded. In leachate, concentration of TP and $\text{PO}_4\text{-P}$ reduced was by 37 and 95%, respectively, when broiler litter was subsurface-banded. The $\text{NO}_3\text{-N}$ concentration was reduced by 43% when broiler litter was subsurface-banded. Similar trends in concentration of nutrients in leachate were seen in the loading of nutrients in leachate. Subsurface application of litter reduced the concentration of TP and $\text{PO}_4\text{-P}$ to control plot levels in surface runoff and leachate. The concentration of TP and $\text{PO}_4\text{-P}$ was less in leachate in comparison with their corresponding concentration in surface runoff. However, since more than 90% of the water infiltrated, the loading of TP and $\text{PO}_4\text{-P}$ was greater in leachate in comparison with loading in surface runoff, irrespective of the treatment. $\text{PO}_4\text{-P}$ and TP loading was about 16 and 43%, respectively, more in leachate than surface runoff. This suggests that loss of phosphorus via subsurface flow is important in this region.

Overall results of this study suggest that subsurface transport of P is as important as surface transport of P. New BMPs need to be developed which can reduce loss of nutrients via subsurface flow to a nearby waterbodies.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Alabama (AL) ranks in the top three US states in broiler production along with Georgia and Arkansas. The poultry industry is critical to many local economies in Alabama, as poultry and its allied industries support more than 80,000 jobs (ACES, 2007). However, this industry is threatened due to water quality problems associated with poultry litter application on pastures. Broiler production in Alabama results in generation of 1.25 million tons of poultry litter annually (Aksoy et al., 2008). This poultry litter generated is commonly used on pastures as an inexpensive alternative to fertilizer. Due to expense of transporting litter, application of poultry litter is confined to the local areas of its production (Moore et al., 1995). This results in repeated application of poultry litter year after year on same areas, such as pastures and agricultural fields. Generally the application of poultry litter is based on the nitrogen (N) requirement of the crop to reduce the nitrate loss by leaching to groundwater (Sharpley et al., 1994). However due to lower N to phosphorus (P) ratio in poultry litter than the N to P ratio required by crops, this practice has resulted in P accumulation in soils. The P content in soils directly impacts P loss in surface runoff. The greater the P concentration present in the soils the more is its loss in surface runoff. The P loss from fields fertilized with poultry litter results in the widespread problem of

eutrophication of near-by surface waters, eventually accelerating the oxidation of organic matter and reducing the dissolved oxygen levels below the respiration requirement of fish, causing fish kills (Carpenter et al., 1998; Edwards and Daniel, 1994).

1.2 SURFACE TRANSPORT OF PHOSPHORUS

Loss of P in surface runoff is one of the major sources of non-point source (NPS) pollution of P. Phosphorus loss from fields depends on different factors such as application rate, application method, and timing of application of poultry litter. The most common method of poultry litter application to pasture is surface application. However pastures thatch, prevents P in poultry litter to be immediately adsorbed by the soil and results in P loss in surface runoff (Schroeder et al., 2004). Previous studies have shown that subsurface application of manure helps in reducing nutrient loss in surface runoff. Ross et al. (1979) showed that injecting dairy manure into the soil reduced N and P losses in surface runoff. Nichols et al. (1994) found subsurface application of poultry litter did not improve runoff water quality from fescue pasture because shallow rotary tillage method used in this study damaged the grass thatch soil cover and did not adequately turn litter under soil surface. They suggested that nutrient loss in runoff might be reduced using a less disruptive method which moves poultry litter below the soil surface. Torbert et al. (2005) showed that incorporation of poultry litter reduces the losses of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ in surface runoff of cultivated land. Incorporation by plowing followed by disking in a Barnes loam soil (fine-loamy, mixed Udic Haploboroll) resulted in P and N losses equal to those in surface runoff from unfertilized soil (Timmons et al., 1973). Pote et al. (2003) also showed that N and P concentration and mass losses were reduced by more than 80% in runoff from incorporated litter than surface-applied litter. In the Sand Mountain region of north AL previous study has shown that more than 90% of the rainfall infiltrates in the soil, which points towards

significant subsurface flows in this region (Sen et al., 2009). In this region, where most of the poultry industry is located, information on the effectiveness of incorporating poultry litter to improve surface runoff water quality on pastures is lacking. Since only 10% of the rainfall contributes to surface runoff, P loss in surface runoff might be less in comparison with other locations. Therefore, the objective of our research was to quantify P loss in surface runoff from surface and subsurface-banded poultry litter.

1.3 SUBSURFACE TRANSPORT OF PHOSPHORUS

Sen et al. (2009) has showed that in the Sand Mountain region of north Alabama, only 10% of the rainfall contributes to surface runoff. Since more than 90% of water infiltrating down through the soil surface, this points towards significant subsurface flow in this region. This large volume of water can transport P via subsurface flow to surface waterbodies. Lysimeters are well accepted instruments used to study the quality and quantity of water in subsurface flow. Different types of lysimeters are used but each type of lysimeter has some advantages and disadvantages associated with it. Monolith soil column weighing lysimeters are capable of accurately monitoring solute concentration and percolate volume, but are not commonly used due to high cost and maintenance (Zhu et al., 2002). Other types of lysimeters commonly used are called suction cup lysimeters. This type of lysimeters has small contact area and requires a continuous source of vacuum for sample collection (Grossmann and Udluft, 1991). These lysimeters also often miss critical solute pulses and cannot measure macropore flow (Barzegar et al., 2004).

Zero tension pan and passive capillary fiberglass wick are other types of lysimeters which are less expensive to install, easier to maintain, disturb the soil less in comparison with monolith

lysimeters, during installation (Zhu et al., 2002). The advantage of a pan lysimeters is that they provide a good way to study the chemical composition of leachate (Jemison and Fox, 1992). The passive wick lysimeters are believed to have better collection efficiencies than pan lysimeters (Zhu et al., 2002). However, effect of wick material on the chemical composition of samples is not known. However if both these lysimeters are used together, they can give an accurate estimate of both quantity and quality of leachate.

The method for installing lysimeters in soil involves excavation of soil pits with a backhoe followed by excavation of the lysimeter tunnels using a gasoline engine auger (Zhu et al., 2002; Jemison and Fox., 1992). Then these lysimeters are installed at a required horizontal distance from the edge of the pit. A steel strip is placed against the ceiling of the tunnel and supported with pressure treated lumber to prevent the ceiling from collapsing. However this method can cause much more disturbance in soil during installation. In this method it is difficult to get tunnels with a uniform ceiling using the gasoline engine auger.

1.4 OBJECTIVES AND HYPOTHESIS

The overall objective of this study is to quantify P loss in surface and subsurface flow from surface and subsurface-banded poultry litter. The experimental site was located in the Sand Mountain region of north Alabama, where most of the Alabama's poultry litter producing counties are located (Cullman, Marshall, DeKalb, and Blount). The repeated application of broiler litter to pastures in this region has resulted in buildup of phosphorus and affects the surface runoff water quality. Specific objectives of this study are:

- 1) To quantify P loss in surface runoff from surface and subsurface-banded poultry litter.
- 2) To develop a method for installation of pan and wick lysimeters in soil.

3) To quantify P loss in subsurface and surface runoff from surface and subsurface-banded poultry litter.

The specific research hypotheses were:

For objective 1:

- Subsurface band application of poultry litter will reduce the P loss in surface runoff in comparison with surface broadcast application of poultry litter.

For objective 3:

- Subsurface transport of P is an important mechanism of P transport in this region because of a large volume of infiltration.

1.5 ORGANIZATION OF THE STUDY

This study focuses on the three objectives mentioned above and each objective is covered in a separate chapter. All three chapters are written in journal format; therefore literature review corresponding to each objective is provided at the beginning of each chapter.

Chapter 2 pertains to the P loss in surface runoff from surface and subsurface-banded poultry litter. Data were used to identify which application method of poultry litter is a better method to control loss of nutrients in surface runoff. This chapter will be submitted to the Journal of Environmental Quality (JEQ).

Chapter 3 pertains to the development of a new method to install pan and wick lysimeters in soil. This chapter will be submitted to Applied Engineering in Agriculture.

Chapter 4 pertains to the P loss in subsurface flow from surface and subsurface-banded poultry litter. The results of P loss in surface and subsurface flow are compared. This chapter will be submitted to the JEQ.

Chapter 5 pertains to the conclusions of this study and recommendations for future work.

CHAPTER 2

**SURFACE TRANSPORT OF PHOSPHORUS FROM SURFACE-APPLIED AND
SUBSURFACE-BANDED POULTRY LITTER**

2.1 INTRODUCTION

Alabama ranks in the top three (after Arkansas and Georgia) broiler producing states in the United States. More than 1.25 million tons of poultry litter (*Gallus gallus domesticus*) are being produced annually by the Alabama broiler production industry (Aksoy et al., 2008). Poultry litter contains many essential nutrients, such as, N, P, K, Ca, Mg, Mn, Cu, and Zn required for plant growth (Wood et al., 1999). With high nutrient value and availability, poultry litter is commonly used as an inexpensive fertilizer on pastures in major poultry producing states. However, application of poultry litter is confined to the local areas of broiler production because of restrictions imposed by the economics of poultry litter transportation (Moore et al., 1995). Major poultry producing counties in Alabama are Cullman, Marshall, DeKalb, and Blount, located in the Sand Mountain Region of north Alabama (Sen et al., 2008). Though poultry litter serves as an inexpensive and good alternative to inorganic fertilizers, degradation of surface water quality because of transport of P from land-applied poultry litter is a concern. Continuous application of poultry litter on the same pastures in this region at P rates exceeding the amount removed by crops has resulted in widespread increases in P levels in the soil. In the past,

application of poultry litter has been based on the nitrogen (N) requirement of the crop to reduce the nitrate loss by leaching to groundwater (Sharpley et al., 1994). The N to P ratio in poultry litter is lower than the N to P ratio required by crops, so this practice has resulted in P accumulation in soils. For example the poultry litter average nutrient composition in AL is approximately equivalent to a 3-3-2 (N-P-K) grade fertilizer (Mitchell and Donald, 1995). The nutrient requirement of fescue pasture is 9-7-1 (Mitchell, 1999), which means application of poultry litter on the N basis will supply extra P than removed by the plant. This accumulation of P has resulted in an imbalance which is not agronomically of concern but is of environmental concern (Sharpley et al., 1996). Application of poultry litter based on P requirement rather than N requirement may help in decreasing the P level in soils and lower the risk of nitrate leaching to groundwater. However, this will result in elimination of large areas for poultry litter application because many years are required for lowering the soil P level. McCollum (1991) estimated that 16 to 18 years would be needed to reduce soil test P (Mehlich-3) in a Portsmouth soil from 100 mg kg⁻¹ to the threshold agronomic level of 20 mg kg⁻¹ without further addition of P when cropping corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr]. In addition, farmers that depend on poultry litter to supply most of the crop N requirement have to buy commercial inorganic fertilizer, which will put economic burden on the farmers (Moore et al., 1995).

The accumulation of P in soils is directly related to its loss in surface runoff. The higher the P level in the soils the higher the dissolved P loss in surface runoff (Cox and Hendricks, 2000 and Hansen et al., 2002). However, P loss from agricultural fields and pastures is not of economic importance to farmers as it is generally about 1 to 2% of the P applied (Sharpley et al., 1999). However, P loss results in off-site environmental impacts, occurring some kilometers away from the P source. P loss from fields fertilized with poultry litter results in a widespread

problem of eutrophication of nearby surface waters, eventually accelerating oxidation of organic matter and reducing dissolved oxygen levels below the respiration requirement of fish, causing fish kills (Carpenter et al., 1998; Edwards and Daniel, 1994). A lake water P concentration of 0.02 ppm is considered as the critical concentration above which the P concentration can cause eutrophication (Sharpley et al., 1999). Phosphorus is considered as the main limiting nutrient for eutrophication (Sharpley et al., 1994; Daniel et al., 1998). Carbon (C) and N are also required for the growth of aquatic biota. It is difficult to control the exchange of C and N between the atmosphere and water, and to control fixation of atmospheric N by some blue green algae, however, so most of the attention is focused on controlling P loss in surface runoff (Daniel et al., 1998).

The forms of P transported in surface runoff are dissolved organic and inorganic P, and particulate P associated with mineral or organic particles (Schroeder et al., 2004). Soil erosion rates from pasture and hay are low, however, so the dissolved fraction of P (DP) is usually the dominant form of P (Sharpley et al., 1992). DP is released from manure, soil, and plant material when rainfall or irrigation water interacts with the top few centimeters of surface soil (Sharpley, 1999). The main processes involved in the loss of DP in runoff is desorption, dissolution, and extraction of P from soil, crop residues, and surface-applied fertilizer and manure (Sharpley et al., 1994). DP is immediately available to aquatic biota for uptake and sediment P is a long term source for aquatic biota (Sharpley, 1993). The loss of P depends upon different factors such as litter application rate, litter application method, time of application of litter, and amount and time of rainfall after manure application (Sharpley et al., 1998).

Surface broadcast of poultry litter to pastures is the most common method of litter application. However poultry litter surface application to pastures has shown high a loss of P in

surface runoff. During surface application of litter to pastures and hayfields, a surface layer of thatch prevents direct contact between litter and soil, which prevents the possibility of P in manure being immediately adsorbed by the soil (Schroeder et al., 2004). Some of the previous studies have shown incorporation of manure reduces nutrient loss in surface runoff. For example, Ross et al. (1979) showed that injecting dairy manure into the soil reduced N and P losses in runoff. Nichols et al. (1994) showed that incorporating surface-applied litter did not improve runoff water quality from fescue (*Festuca arundinacea Schreb*) pasture because the shallow rotary tillage method they used damaged the grass thatch soil cover and did not adequately put the litter beneath the soil surface. They suggested that nutrient loss in runoff might be reduced using a less disruptive method which moves poultry litter below the soil surface. Torbert et al. (2005) showed that subsurface application of poultry litter reduces the losses of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ in surface runoff from cultivated land. Incorporation of fertilizer by plowing followed by disking in a Barnes loam soil (fine-loamy, mixed Udic Haploboroll) resulted in P and N losses equal to those in surface runoff from unfertilized soil (Timmons et al., 1973). Pote et al. (2003) also showed that N and P concentration in runoff water and N and P mass losses in runoff were reduced by more than 80% from incorporated poultry litter, compared to surface-applied litter. In Sand Mountain Region of north Alabama, a previous study by Sen et al. (2009) has shown that only 10% of the rainfall contributes to surface runoff. This may result in significantly less loading of nutrients in surface runoff in comparison with other regions. Some plot scale studies have been done to quantify P loss in surface runoff from surface and subsurface-banded poultry litter (Pote et al., 2003; Sistani et al., 2009). To date, information on the effectiveness of incorporating poultry litter to improve surface runoff water quality on pastures in the Sand Mountain Region of north Alabama where more than 90% of the rainfall

infiltrates is lacking. Therefore the objective of our research was to quantify phosphorus loss in surface runoff from surface and subsurface-banded poultry litter.

2.2 MATERIALS AND METHODS

2.2.1 Plot Setup, Soil Sample Collection, and Poultry Litter Application

The nine 3.05 m by 1.52 m (10 ft by 5 ft) plots used for the experiment were constructed on a Hartsells (fineloamy, siliceous, subactive, thermic, Typic Hapludults) soil at the Alabama Agricultural Experiment Station's Sand Mountain Research and Extension Center at Crossville, AL (Fig. 2.1). This type of soil is moderately deep (sandstone at 50-100 cm), well drained, moderately permeable, and is formed from acid sandstone (Sen et al., 2008). These soils are found on upper slopes of hills and mountains and on level to moderately steep ridges. Each plot had a uniform slope of 4% along the long axis and was cross leveled. All the plots had galvanized steel sheet metal borders (10 cm belowground and 10 cm aboveground) to isolate runoff. A galvanized steel sheet metal trough attached to a 10 cm horizontal approach sheet metal plate, on the upslope side of the trough, was installed at the downslope end of the plot to collect surface runoff and convey it to a collection point at the corner of the plot. The plots were constructed on tall fescue (*Fescue Arundinacea Schreb.*) pasture that was mowed to the height of 10 cm before the experiment. Before application of broiler litter three baseline soil samples were collected at five different depths, i.e., 0-5, 5-15, 15-25, 25-40, and 40-50 cm for each plot. The nutrient content of the top 0-5 cm soil layer is shown in Table 2.1. The results of the soil P level at five different depths were used to show the overall depth distribution of P. These samples were collected 2-3 cm outside the sheet metal borders so that hydrology of the areas inside the plot would not be disturbed. The soil samples were analyzed for pH, moisture content, Mehlich-1 extractable P (M1-P), water extractable P (WEP), total Kjeldahl N (TKN), ammonium N (NH₄-

N), and nitrate N (NO₃-N). Broiler litter used for the experiment was collected from a local poultry house. Samples of broiler litter were taken before application to the plots and stored in a plastic bag at 4 °C until analyzed. These samples were analyzed for water content, pH, electrical conductivity (EC), TN, TP, NH₄-N, NO₃-N, and PO₄-P (Table 2.2).

Out of nine plots, three plots were used as control plots (no litter application), three plots for surface broadcast of litter, and three plots for subsurface band application of litter. Treatments were assigned in a randomized pattern to all the plots. Broiler litter for the plots with surface application of litter was broadcasted manually as uniformly as possible over the entire plot. For subsurface application of broiler litter, a subsurface band applicator (Fig. 2.2) was used. This applicator was developed by the USDA-ARS National Soil Dynamics Laboratory, Auburn, AL. Using this applicator, on each subsurface band application plot, nine subsurface band trenches about 5 cm deep and 4 cm width were made, with each trench extending across the width of the plot. These trenches were spaced at an interval of 30.5 cm. The appropriate amount of broiler litter was placed in each trench. Soil that had been heaved-up along the sides of each trench when the trench was formed, was then pressed back in on the top of the trench, thereby covering the litter band with soil to prevent any direct contact between surface runoff water and the broiler litter. A broiler litter application rate of 5.0 Mg ha⁻¹ was used for each treatment plot.

2.2.2 Rainfall Simulator Experiment

A rainfall simulator with one TeeJet ½ HH-SS50WSQ nozzle (Spraying Systems Co., Wheaton, IL) was used to conduct rainfall simulations on each plot. This nozzle was fixed at the center of the simulator which was 305 cm above the soil surface. The aluminum frame was fitted with tarps to provide a windscreen (Fig. 2.3). The pressure gauge and water piping were mounted on the aluminum frame. Before conducting rainfall simulations on plots, the rainfall

simulator was calibrated at different pressures to get the required rainfall intensity. Fifteen cylindrical cans which were about 101 mm in diameter were placed on the soil surface below the rainfall simulator in a grid pattern and rainfall simulation was conducted for 10 minutes. The volume collected by each can was measured. The same procedure was repeated at different water pressures. Based on the calibration we used 35 kPa (5 psi) as our target pressure to conduct rainfall simulation at an intensity of 70 mm h⁻¹ on all the plots. During the experiment National Research Project for Simulated Rainfall – Surface Runoff Studies Protocol was followed (National Phosphorus Research Project, 2005). The rainfall simulation was conducted at an intensity of 70 mm h⁻¹ based on the 1 h, 10 year return period of that area. On an average it took about 40 minutes on each plot for the start of runoff. One-liter of runoff samples were collected every 5 min for 1 h, starting 2.5 min after the start of runoff (Fig. 2.4). Runoff flow rate was estimated by recording the time to fill a 1 L of sample bottle. Total runoff volume from each plot was also collected in a large bucket from each plot. The volume of water infiltrated into the soil was determined by subtracting the runoff from the volume of rainfall for the entire rainfall simulation period. Immediately after runoff sample collection, samples were stored at 4 °C until they were analyzed. Samples of the water flowing from the rainfall simulator nozzle were also collected and analyzed before the experiment. All the water samples results discussed later on represent the mean of three replications (3 plots).

2.2.3 Chemical Analysis of Soil, Litter, and Water Samples

The soil samples collected were analyzed for nutrients at the Auburn University, Agronomy and Soils Department, Nitrogen Laboratory. Soils were dried at 60°C for 48 h and sieved through a 2 mm sieve before analyzing them for different nutrients. NH₄-N and NO₃-N were extracted by taking 5 g of a soil sample using 2 M KCL (Keeney and Nelson, 1982) and

were analyzed using the microplate procedure (Sims et al., 1995). To analyze WEP, 2 g soil was placed in a 40 mL centrifuge tube and extracted with 20 mL of distilled water for 1 h on a mechanical shaker (Self-Davis et al., 2000). After each sample was centrifuged, aliquots were filtered through a 0.45 μm membrane and acidified to pH 2 with HCl. Water extractable P (WEP) was then determined calorimetrically (Murphy and Riley., 1962). For Mehlich 1 extractable P measurement, 5 g of a sample was extracted with 20 mL of a dilute double acid mix of 0.05 N HCl and 0.025 N H₂SO₄ (Hue and Evans, 1986) prior to analyses via inductively coupled argon plasma (ICAP) spectroscopy (Spectro Ciros CCD, Side on Plasma, Germany).

For analysis of NH₄-N and NO₃-N in broiler litter, a similar method was used as for soil samples, except instead of using 5 g, 1 g of finely ground (1 mm mesh) broiler litter sample was used. TP in litter was determined by dry ashing method (Hue and Evans., 1986). In this, 0.5 g broiler litter was heated in a muffle furnace at 450 °C for 4 h. This was followed by addition of 10 mL of 1 N HNO₃ to evaporate to dryness. Ten mL of 1 N HCl was then added to dissolve the residue. Broiler litter and soil were analyzed for organic C and Total N by dry combustion (LECO TruSpec CN, LECO Corp., St. Joseph, MI). Measurements of pH were done for soil (1:1 soil:water) and broiler litter (1:3 litter:water) using a pH meter (Denver instrument UB-5, Arvada, CO).

Water quality samples filtered with a 0.45 μm filters were analyzed for NH₄-N, NO₃-N, and PO₄-P, while unfiltered water samples were analyzed for TP. NH₄-N and NO₃-N were measured on filtered samples using microplate procedure (Sims et al., 1995). PO₄-P was measured using the colorimetric method (Murphy and Riley, 1962). For TP analysis, 25 mL of unfiltered water sample was digested with 10 mL of wet ash acid mix (70:30 nitric:perchloric

acid) (John, 1972) prior to analysis ICAP spectroscopy (Spectro Ciros CCd, Side on Plasma, Germany).

Analyses of variance were done using PROC GLM of SAS programs (SAS Institute, Inc., 1999) was used to perform analysis of variance (ANOVA) using PROC GLM procedure. To separate means of experimental results, the least significant difference (LSD) was used. Unless otherwise noted, all the statistical tests were performed at the $\alpha = 0.05$ significance level.

2.3 RESULTS AND DISCUSSION

2.3.1 Water Budget

The water budget of the entire experiment is shown in Table 2.3. The percentage of rainfall that contributed to 1 h of runoff was less in plots with subsurface-banded litter in comparison with control and surface-applied litter plots. The likely reason for this is that some amount of water was absorbed by broiler litter, so some of the water stayed in the trenches where broiler litter was applied. For the control plots, a greater percentage of rainfall contributed to surface runoff, than for the surface-applied litter plots as the control plots were without broiler litter and trenches. In surface-applied litter plots, the percentage of rainfall which contributed to surface runoff was between that of the control and that of the subsurface-banded litter plots. Since these surface-applied and control plots were without trenches, this likely caused a greater percentage of rainfall to contribute to surface runoff, compared to the subsurface-banded litter plots. Some amount of water might have been absorbed by the broiler litter, which resulted in a smaller percentage of rainfall contributing to surface runoff than for the control plots. Though there were variations between rainfall applied and runoff generated within different treatments, these differences were not significant at $\alpha = 0.05$ (Table 2.3). Irrespective of treatment to plots,

results showed that less than 10% of the rainfall contributed to surface runoff in all plots. This result supports the previous study by Sen et al. (2009) that in the pastures of the Sand Mountain region of north Alabama less than 10% of the rainfall contributes to surface runoff. In all the plots more than 90% of the water infiltrated down into soil which was not significantly different ($\alpha = 0.05$) among all plots. This suggests that significant subsurface flow occurs in this region, irrespective of the treatment. Therefore transport of nutrients in this region via subsurface flow may be important.

2.3.2 Runoff Concentration

Nutrient concentrations are defined as the flow-weighted nutrient concentrations (i.e., mass of nutrient loss in 1 h of runoff divided by total volume of runoff in a given time). The mean flow-weighted concentrations of the nutrients analyzed in surface runoff were strongly affected by broiler litter application method (Table 2.4). Runoff from surface-applied litter plots had the greatest concentrations of all nutrients. Nutrient concentrations were significantly higher ($\alpha = 0.05$) in the surface runoff of surface-applied litter plots in comparison with subsurface-banded litter and control plots. TP and $\text{PO}_4\text{-P}$ concentration was reduced by 83 and 88%, respectively, in surface runoff when broiler litter was subsurface-banded compared to the surface-applied litter. The TP concentration followed the same trend as $\text{PO}_4\text{-P}$ concentrations in all the plots. Our data shows that $\text{PO}_4\text{-P}$ is the dominant form of TP in surface runoff from tall fescue pasture. Nichols et al. (1994) reported similar results that $\text{PO}_4\text{-P}$ constitutes more than 50% of TP in surface runoff from surface-applied and subsurface-banded litter plots. Subsurface band application of litter also reduced the N concentration in surface runoff. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations were reduced by about 80 and 74%, respectively, in surface runoff from subsurface-banded litter plots in comparison with surface-applied plots. The concentrations of

all nutrients in subsurface-banded litter plots were very close to that of the control plots; there were no significant differences ($\alpha = 0.05$) found in nutrient concentrations between control and subsurface-banded litter plots. The nutrient concentration results show that subsurface band application of litter proved to be a better method to control nutrient concentrations in surface runoff in comparison with surface broadcast application of litter. This is because subsurface band application of litter prevents the direct contact between broiler litter and surface runoff as surface runoff water interacts with the top few cm of soil. A previous study by Sharpley et al. (1985) also showed that effective depth of interaction between surface soil and surface runoff is the upper 2.5 to 5 cm.

2.3.3 Mass Loss in Surface Runoff

Mass loss (loading) in runoff was determined by taking the product of concentration of each discrete sample and the corresponding flow volume and summing up these incremental loads for the entire runoff duration. The mean loading of runoff constituents i.e. TP, PO₄-P, NH₄-N, and NO₃-N also differed among different treatments (Fig. 2.5 & 2.6). The trends similar to concentration was observed in loading of nutrients from different plots. Significantly ($\alpha = 0.05$) greater loading of nutrients (TP, PO₄-P, NH₄-N, and NO₃-N) in runoff was observed from plots with surface-applied litter in comparison with subsurface-banded. TP and PO₄-P loading was about 83 and 88% more in surface runoff from surface-applied litter plots than subsurface-banded plots. There was no significant difference ($\alpha = 0.05$) found in loading of TP and PO₄-P between control and subsurface-banded litter plots. In a similar study by Sistani et al. (2009) also found out that loading of nutrients significantly reduced in surface runoff when poultry litter was subsurface applied. However TP loading in surface runoff 1-d after poultry litter application, reported by them was much greater than our study. The TP loss was about 80 and

50% more in surface-applied and subsurface-banded litter plots, respectively. The reason for this might be the application rate used by them was 8.97 Mg ha^{-1} in comparison with the 5 Mg ha^{-1} used in our study. The other reason for this might be the rainfall intensity at which they carried out the rainfall simulation was 110 mm h^{-1} which might have resulted in loss of more poultry litter in runoff sample in comparison with our study which was carried out at an rainfall intensity of 70 mm h^{-1} . The TP loss in surface runoff of surface-applied litter plots was 1.1% of the sum of the initial P in the soil and the P added by broiler litter (Fig. 2.7). The percentage of TP loss in surface-applied litter plots was significantly higher than that of the control and subsurface-banded litter plots (Fig. 2.7). In the case of the control and subsurface-banded litter plots, the TP loss was less than 1% of the initial TP in the plot. To calculate the initial TP in the case of the subsurface-banded litter plots, the TP in broiler litter was not taken into consideration, as surface runoff interacts with the top 2.5 to 5 cm of soil. In the case of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, loading in the surface runoff was reduced by 74 and 81% respectively, in subsurface-banded litter plots in comparison with surface-applied plots. There was no significant difference observed in the loading of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ between the subsurface-banded litter and the control plots. Though in field experiments significant difference in loading of nutrients are difficult to detect. This is because loading is the product of runoff volume and the mean concentration of that constituent in the runoff. Each of these factors has considerable variation in field situations, so this results in greater variation in their product. However, in our case the product of runoff volume and mean concentration was less in subsurface-banded litter plots than in the other plots. Though there was no significant difference ($\alpha = 0.05$) in runoff volume among the three treatments, the concentration of nutrients in the runoff of the subsurface-banded litter and control plots was significantly less than for the surface-applied litter plots. This decrease in the

concentration of nutrients decreased made the product of runoff volume and concentration less. Thus a significant difference was observed in loading between different treatments, and in our case, and the trend followed the same trend as was followed by the concentrations.

There standard deviations of the loading and of the concentration of nutrients from plots with surface-applied litter were greater than for the control and subsurface-banded litter plots. The reason for more variation in the loading from surface-applied plots might be the presence or absence of broiler litter in samples coming from surface-applied litter. In some samples, even if a small amount of broiler litter gets in the runoff sample, it can increase the loading and concentration by a much greater amount in comparison with samples containing without or less broiler litter or no broiler litter. The standard deviations for the control and subsurface-banded plots were less than those of the surface-applied litter plots. This might be because, in the case of these plots the loading and concentration resulted from the top layer of soil which didn't have much variation in the initial soil P level.

2.3.4 Depth Distribution of Mehlich-1 Extractable Phosphorus

Depth distributions of Mehlich 1 extractable P (M1-P) in soil indicate that the M1-P level was greatest at the soil surface and decreased as the depth increased in all the plots. Mean depth distribution of initial M1-P level in all plots used for the rainfall simulation is shown in Figs. 2.8, 2.9, & 2.10. The average of the M1-P levels in soil in all three treatments was 37.4 mg kg^{-1} in the top 5 cm of soil and 2.48 mg kg^{-1} in the 40-50 cm depth range. The M1-P level was greatest at the soil surface and decreased as depth increased in all the plots. This relatively high level of M1-P near the soil surface likely resulted from long term application of poultry litter here in the Sand Mountain region of north Alabama. Repeated application of poultry litter has caused the

M1-P level to be greater than the plant requirement level and greater than the adsorption capacity of the soil, and this may have caused leaching of M1-P. Similar results were reported by Kingery et al. (1994) in this region.

2.4 CONCLUSIONS

The results of this study indicate that the method of litter application plays an important role in the concentration and loading of nutrients in surface runoff. Runoff from plots with surface-applied litter had significantly ($\alpha = 0.05$) higher concentrations of nutrients in comparison with subsurface-banded litter plots. Since subsurface application of litter prevents direct contact between poultry litter applied in trenches and surface runoff, the runoff nutrient concentrations in subsurface-banded litter were very close to those of the control plots. There was no significant difference of nutrient concentrations between control and subsurface-banded litter plots. The trend for loading of various nutrients in runoff was similar to the trend for concentration in runoff. Loading of nutrients in surface runoff of surface-applied litter plots was significantly ($\alpha = 0.05$) higher than for subsurface-banded litter plots. There was no significant difference between loading of nutrients from subsurface-banded litter and control plots. The water budget results signify that little runoff is generated in this region. Regardless of the treatment to plots, less than 10% of the rainfall contributed to surface runoff. Since more than 90% of the water infiltrates down into the soil, this points to significant subsurface flows in this region. Because of the large volume of water infiltrating down in the soil, it is important to take subsurface flows into consideration. Subsurface transport of nutrients can be more than surface transport of nutrients, considering the volume of water infiltrating down. Therefore, future studies should be done in this region to quantify nutrient loss via subsurface flows.

The results show that subsurface band application of litter is a better method compared to surface broadcast application of litter, With regard to reducing phosphorus in surface runoff. However, subsurface transport of litter P under these two litter application methods needs to be quantified.

Table 2.1. Selected properties of soil for the 0 to 5 cm depth before the litter application.

Parameter	Value*
pH	5.13 (0.02) [†]
NH ₄ -N (mg/kg)	21.59 (0.67)
NO ₃ -N (mg/kg)	13.22 (0.79)
TN (%)	0.14 (0.19)
M1-P (mg/kg)	37.37 (0.45)
PO ₄ -P (mg/kg)	4.61 (0.67)

* Mean of 27 samples

[†] Coefficient of variation

Table 2.2 Composition of broiler litter applied to tall fescue pasture plots.

Parameter	Value
pH	8.69
NH ₄ -N (mg/kg)	1203.15
NO ₃ -N (mg/kg)	110.77
TN (%)	2.94
TP (mg/kg)	19278.36
PO ₄ -P (mg/kg)	3114.43

Table 2.3. Water budget for the experiment showing amount of rainfall applied, runoff generated, volume of water infiltrated, and percentage of rainfall which contributed to runoff and infiltration.

	Litter Treatment		
	Control plots	Surface-applied litter plots	Subsurface-banded litter plots
Rainfall (m ³)	0.56a	0.51a	0.58a
Runoff (m ³)	0.05a	0.04a	0.04a
Infiltrated (m ³)	0.51a	0.46a	0.53a
Percentage of rainfall contributed to runoff	8.9	7.8	6.9
Percentage of rainfall infiltrated	91.1	92.2	93.1

Within each row means followed by the same letter are not significantly different at $\alpha = 0.05$ (LSD)

Table 2.4. Flow-weighted concentrations of selected constituents in surface runoff from tall fescue control, surface-applied, and subsurface-banded litter plots

Runoff constituent	Control plots	Surface-applied litter plots	Subsurface-banded litter plots
		mgL ⁻¹	
NH ₄ -N	0.43 a (0.09)†	1.67 b (0.58)	0.33 a (0.09)
NO ₃ -N	0.40 a (0.06)	3.25 b (1.41)	0.83 a (0.03)
PO ₄ -P	0.37 a (0.11)	3.43 b (1.43)	0.42 a (0.08)
TP	0.69 a (0.18)	6.01 b (0.58)	1.02 a (0.03)

¥ Within each row means followed by the same letter are not significantly different at $\alpha = 0.05$ (LSD).

† Standard Deviation

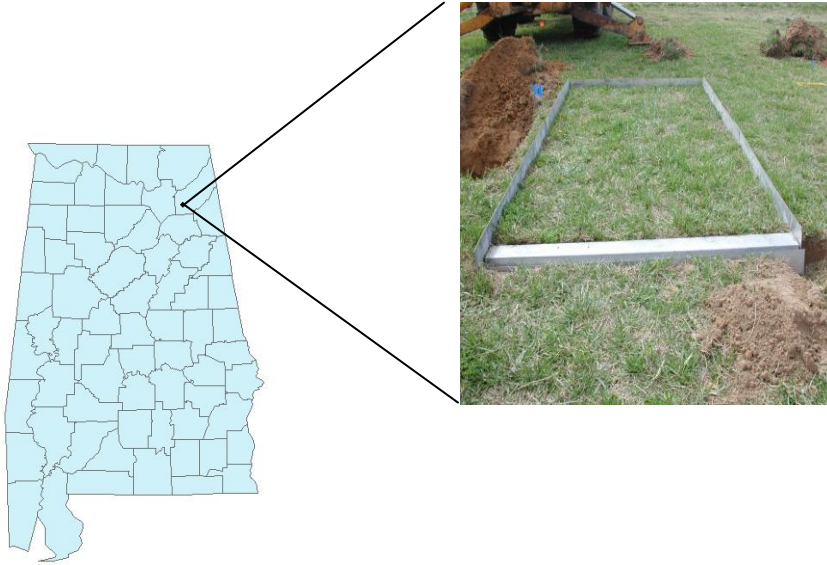


Fig. 2.1. Map of Alabama showing one of the plots used for the experiment. The plots were located at the Alabama Agricultural Experiment Station's Sand Mountain Research and Extension at Crossville, AL.



Fig. 2.2. Rear view of subsurface band applicator used to make trenches in plots for subsurface band application of broiler litter.



Fig. 2.3. Rainfall simulator, covered with tarps, on a plot during rainfall simulation.



Fig. 2.4. Runoff sample collection at the downslope end of each plot.

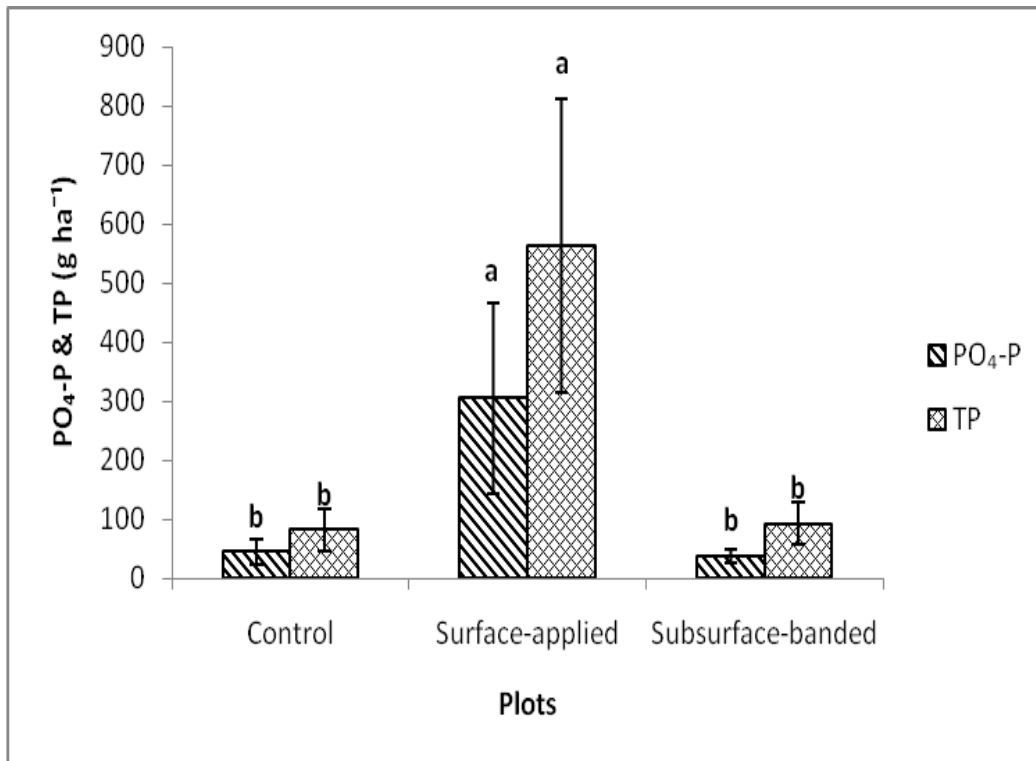


Fig. 2.5. PO₄-P and TP loading in surface runoff from control, surface-applied, and subsurface-banded litter plots. Total bar length is two standard deviations.

Bars with same letter and same nutrient indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

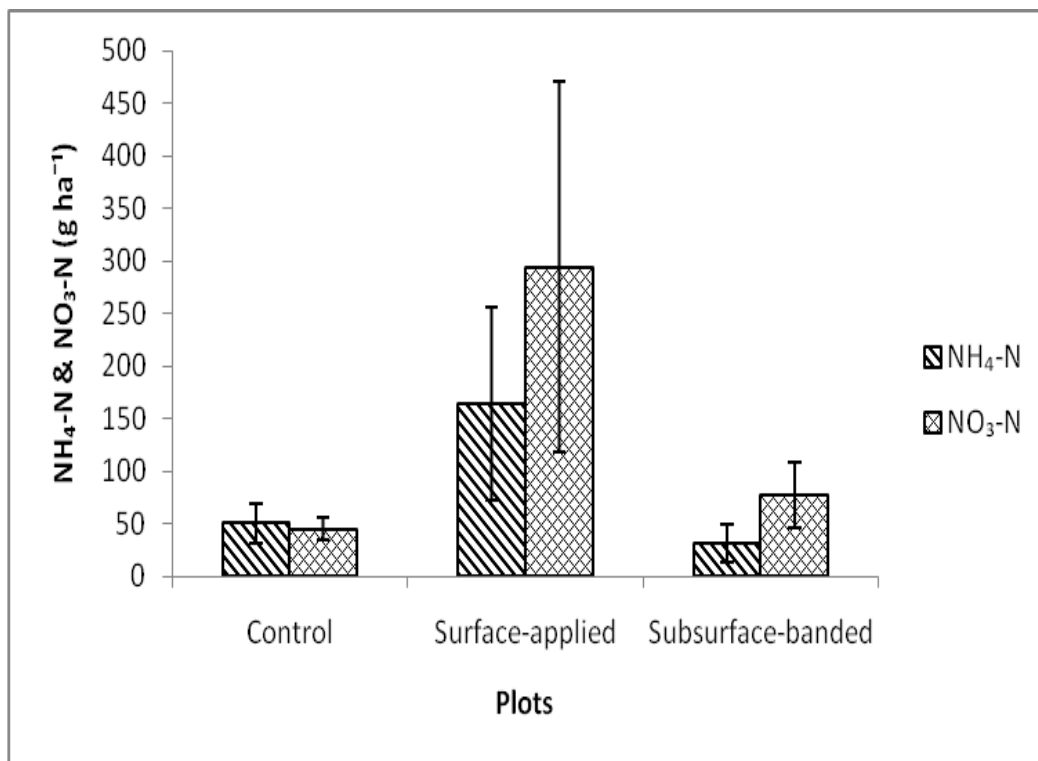


Fig. 2.6. NH₄-N and NO₃-N loading in surface runoff from control, surface-applied, subsurface-banded litter plots. Total bar length is two standard deviations.

Bars with same letter and same nutrient indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

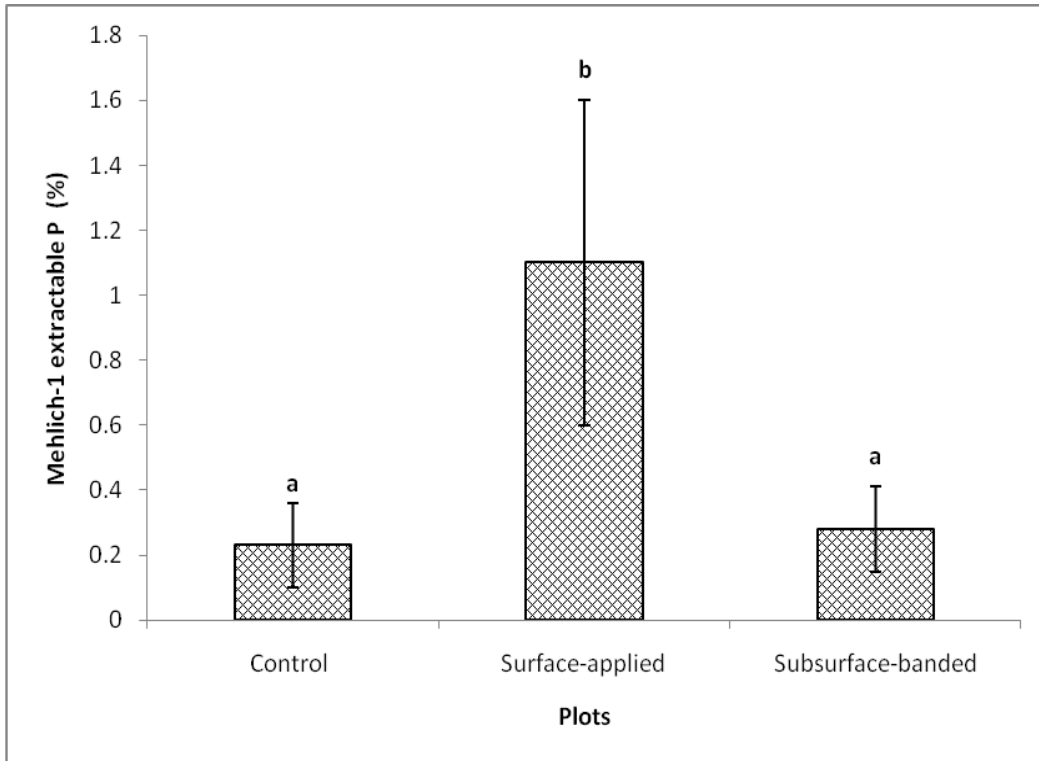


Fig. 2.7. Percentage of Mehlich-1 extractable P loss in surface runoff from control, surface-applied and subsurface-banded litter plots. Total bar length is two standard deviations. Bars with same letter indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

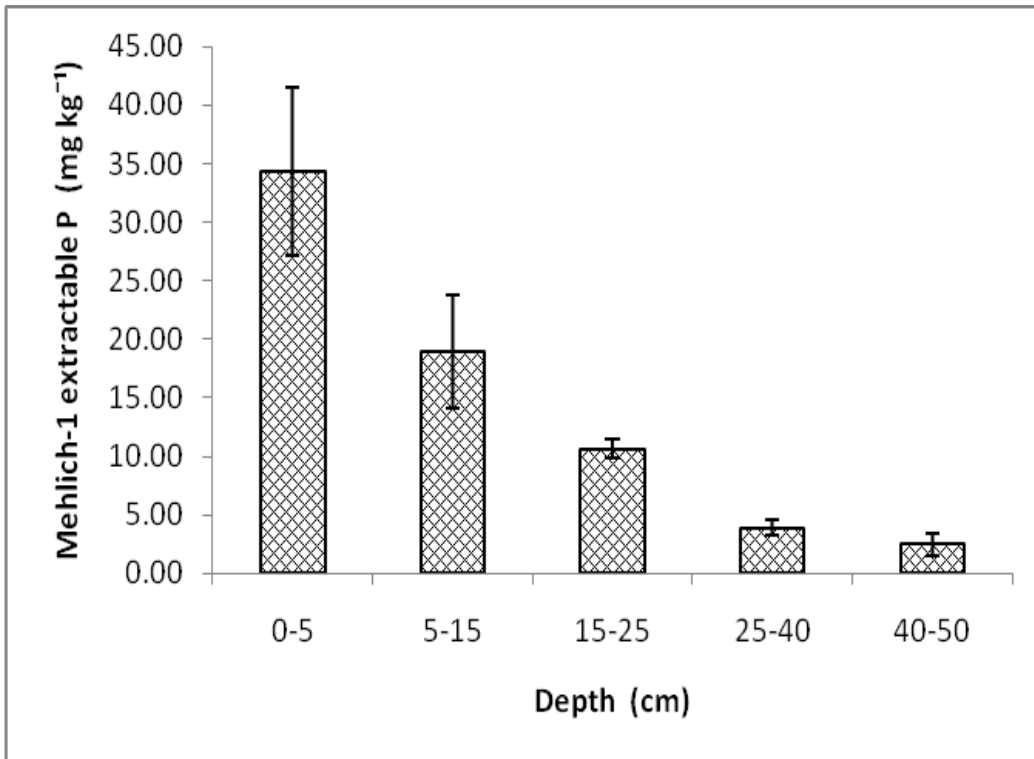


Fig. 2.8. Depth distribution of Mehlich-1 extractable P in plots used for surface broadcast of litter. Total bar length is two standard deviations.

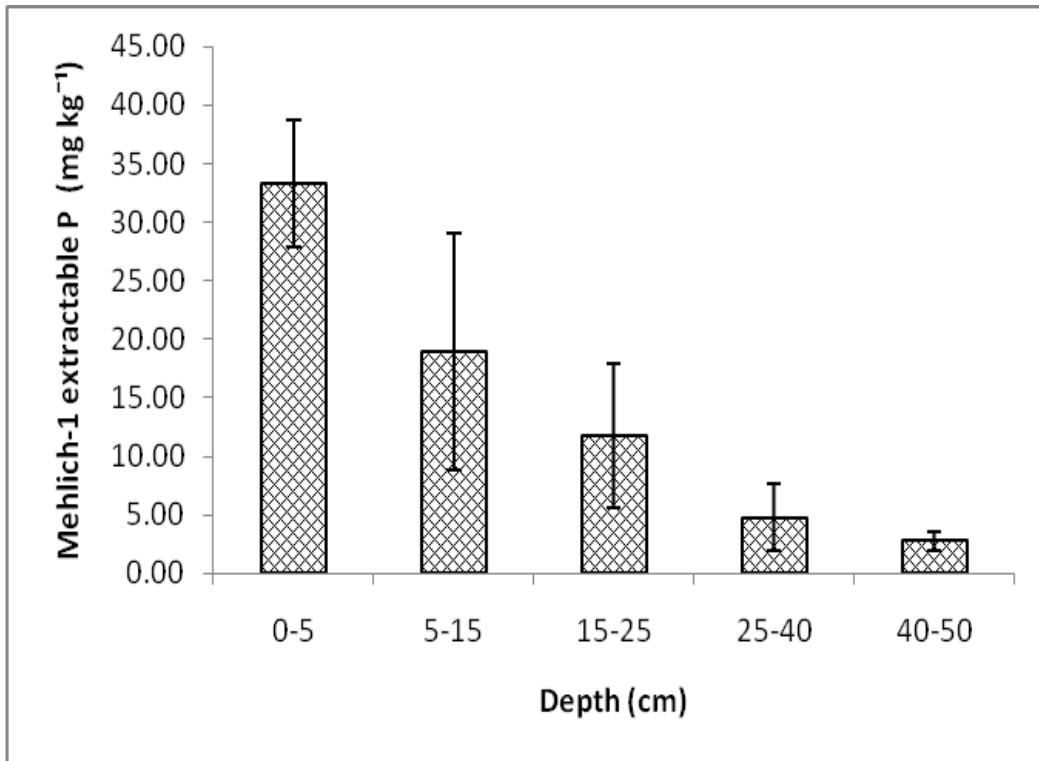


Fig. 2.9. Depth distribution of Mehlich-1 extractable P in plots used for subsurface band application of litter. Total bar length is two standard deviations.

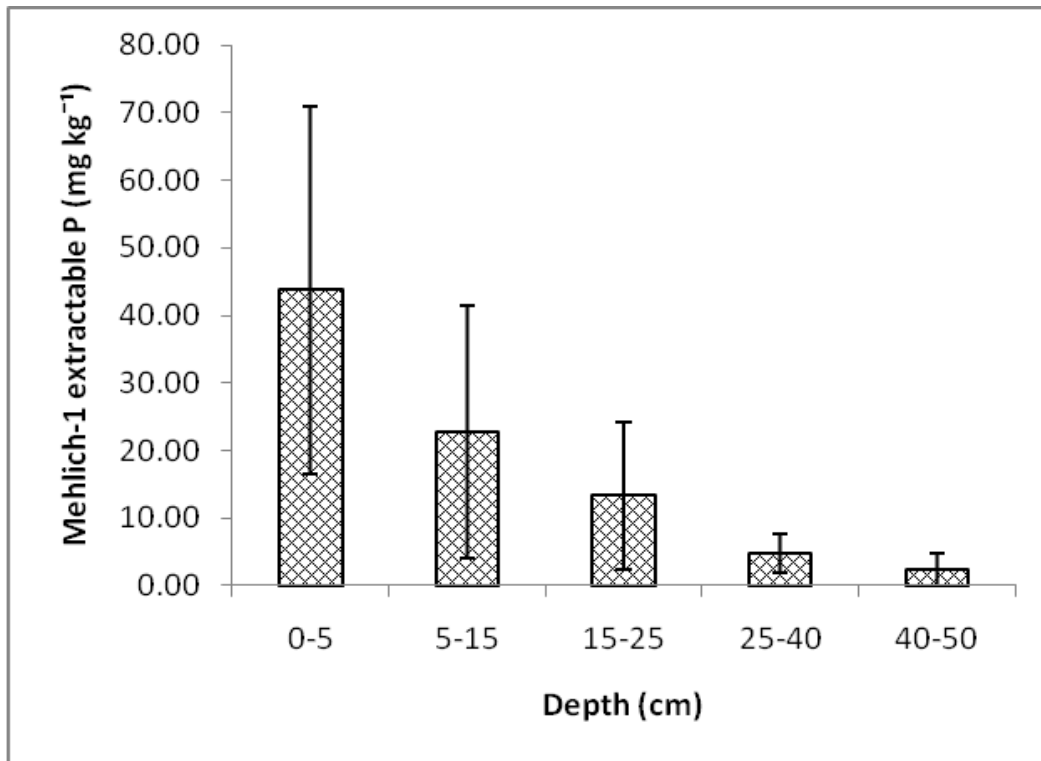


Fig. 2.10. Depth distribution of Mehlich-1 extractable P in control plots.

Total bar length is two standard deviations.

CHAPTER 3

A METHOD FOR INSTALLING ZERO-TENSION PAN AND WICK LYSIMETERS IN SOIL

3.1 INTRODUCTION

Lysimeters are well accepted by soil scientists and hydrologists as field equipment for studying the quality and quantity of water moving down in a soil profile. Various types of lysimeters are available, but all lysimeters have limitations. Therefore, depending upon the objectives of a study, different type of lysimeters can be used. Monolith soil column weighing lysimeters are known to measure solute concentration and percolate volume accurately, but their construction and maintenance cost is high (Zhu et al., 2002). Suction cup samplers require a source of vacuum to draw water from soil pores into a cavity of a sampler (Holder et al., 1991). These types of samplers are also unable to sample water moving through macropores (Shaffer et al., 1979). Soil coring is another method used to collect leachate. However this method is labor intensive, destructive, and does not allow repeated sampling of the same site (Brandi-Dohrn et al., 1996 and Barzegar et al., 2004). Another type of lysimeter which is commonly used is called equilibrium tension lysimeter (ETL) (Brye et al., 1999). These lysimeters measure the soil-water matric potential adjacent to lysimeters by making use of heat dissipation sensors. However these require the human operator to manually adjust ETL suction to match that of the surrounding soil two to three times per week and these lysimeters are also prone to error due to fluctuations in soil water matric potential that occur inbetween adjustments (Brye et al., 1999). Zero-tension pan

lysimeters provide both mass and concentration measurements but have low collection efficiency and large variations in volumes of leachate (Jemison and Fox, 1992). These lysimeters depend on only gravity to cause water movement through them. They collect leachate from only the macropores and only when soil above the pan is saturated (Barbee and Brown, 1986; Brye et al., 1999; Zhu et al., 2002). Passive capillary wick lysimeters (Holder et al., 1991) are known to have a high collection efficiency in comparison with pan lysimeters and collect approximately 100% of soil percolation water (Zhu et al., 2002). However the effect of the wick material on the chemical composition of samples collected by these lysimeters is not well known (Goyne et al., 2000). Use of pan and wick lysimeters together can provide accurate estimates of the quantity and quality of leachate.

Previous work (Zhu et al. (2002) and Jemison and Fox (1992)) showed that for the installation of lysimeters, pits are excavated in soil using a backhoe, followed by excavation of the lysimeter tunnels in the soil using a gasoline engine auger. The lysimeters were then installed inside the soil tunnel at a required distance from the edge of the pit. A steel strip was placed against the ceiling and supported with pressure treated lumber to prevent the ceiling from collapsing. Using the above described method to install lysimeters can cause relatively high much more disturbance in the soil and it will be difficult to get the upper surface of the lysimeter contacting undisturbed and uniformly leveled soil by using an auger.

Our objective was to develop a method for installing wick and pan lysimeters in soil with the top of the lysimeters placed at the depth of 500 mm while minimizing disturbance to the soil and providing the support structures to hold the soil in its place and to get the undisturbed surface of soil in contact with the upper surface of each lysimeter. The purpose of the overall project was to determine water quality and water quantity for runoff and for leachate down

through the soil profile, in field plots on which tall fescue grew. Broiler litter is a mixture of manure from broiler chickens (*Gallus gallus domesticus*) and a bedding material. Broiler litter was applied to three plots using broadcast application to the surface of the plot and to three plots using application in shallow subsurface bands similar to the application by the prototype litter applicator implement developed by the USDA-ARS National Soil Dynamics Lab (Auburn, Ala.) and described in Tewolde et al. (2009) and Farm Show Publishing, Inc. (2009). The particular method used for subsurface band application of litter to the plots is described in Lamba (2009). The remaining three plots in the project were "control" plots, and had no litter applied.

3.2 MATERIALS AND METHODS

The apparatus and procedure described here were used for installing 18 lysimeters in nine tall fescue field plots at the Alabama Agricultural Experiment Station's Sand Mountain Research and Extension Center at Crossville, Ala. The soil was a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults) and the slope of the plots was 4%.

This article describes an apparatus and procedure used for installing pan and wick lysimeters (Fig. 3.1) in soil beneath the surface of the plots, for collecting leachate. The upper portion of each pan lysimeter was a pan constructed of stainless steel and Plexiglas thermoplastic (Fig. 3.1). The pan was filled with polypropylene beads and when the lysimeter was installed in the soil, the upper surface of the beads was horizontal and pressed upward against a horizontal soil surface. The dimensions of the stainless steel frame, which was the perimeter of this upper surface, were 330 mm x 480 mm and the dimensions of upper surface of the polypropylene bead area within that frame, which was the bead area that contacted the soil, were 280 mm x 430 mm.

The pan lysimeter was designed with a sloping bottom that allowed water to flow to one corner of the pan. From this corner, an outflow port covered with polypropylene mesh drained water through polypropylene tubing to a 9.5 L carboy. The beads helped in easy interception of drainage water and diversion of the water to the outflow port. The design of the wick lysimeters was adapted from Holder et al. (1991) and the upper surface of the wick material of each wick lysimeter was 300 mm x 300 mm (Fig. 3.1). The horizontal layer of wick material rested on a horizontal Plexiglas thermoplastic plate. The wick material extended down through a 32 mm diameter hole in the center of the plate and the wick was within a polypropylene tube, which conveyed the leachate to a 9.5 L carboy.

Each of the lysimeters had four turnbuckles to adjust the height of the lysimeters to bring the upper surface of the lysimeters in contact with the tunnel ceiling. During the preliminary tests we found that these turnbuckles were difficult to reach with the lysimeter inside the tunnel. So instead of using the turnbuckles we decided to use two scissor jacks per lysimeter which were easily accessible inside the tunnel using a long handled crank.

The layout of plots and the soil pits between plots is shown in Fig. 3.2. The soil pits allowed insertion of the lysimeters into tunnels that were dug horizontally, perpendicular to the downslope direction, from the pit, in beneath the plot. Our target locations of the pan and wick lysimeters relative to a plot are shown in Fig. 3.3. We tunneled horizontally into the soil beneath the plot, both from the wick lysimeter side and the pan lysimeter side of the plot and then placed the lysimeters in these tunnels. To form each tunnel, steel boxes were built to help support the walls and upper surface of the tunnel. We designed and built a guiding frame to push the steel boxes horizontally into the soil (Fig. 3.4).

3.2.1 Steel Boxes and Guiding Frame

For each lysimeter, we used the guiding frame to insert a steel box, the lysimeter box (Fig. 3.5), into the soil. To get this lysimeter box into its installed position, a pushing box, which was a second steel box, was used for pushing the lysimeter box into the soil. The lysimeter boxes and pushing boxes were constructed using 3 mm thick steel plates.

The first step of installing a lysimeter box in the soil was to place the box on the guiding frame and adjust the height of the frame to get the upper surface of the box to be 500 mm beneath the soil surface of the plot and to get the upper surface of the box level (Fig. 3.6). This was done by adjusting the four vertical threaded rod legs of the guiding frame (Fig. 3.6). When the pan and wick lysimeters were installed within the lysimeter boxes, the upper surfaces of the lysimeters were therefore level. Also, before pushing a box into the soil, the backstop plate was placed behind the guiding frame (Fig. 3.4). This was done to distribute the force from the guiding frame over a relatively large area of the pit wall. This plate helped to keep the guiding frame at the same position during installation of the boxes.

The guiding frame was equipped with a double-acting hydraulic cylinder powered by a tractor hydraulic system, to push the steel boxes into the soil (Fig. 3.7). The cylinder had a 102 mm bore and a 203 mm stroke, and was rated for 17.2 MPa continuous working pressure. For safety, the tractor was parked close to the pit so the tractor operator could see the hydraulic cylinder of the guiding frame and the hands of the person who worked with the guiding frame, the steel boxes, and other components (Fig. 3.7).

The guiding frame had an upper frame section whose height was adjustable relative to the lower frame section. This provided an adjustable height of the hydraulic cylinder relative to the

lysimeter box or pushing box, to allow pushing of the box at an appropriate vertical location on the box. Also, the overall height of the guiding frame was adjustable using the four threaded rod legs (Fig. 3.6). The lower end of each leg was equipped with a base plate.

A pushing frame (Fig. 3.8) was placed against the trailing edge of the lysimeter box (Fig. 3.9). Components from an automotive body repair kit (Omega 10 ton (89 kN) Body Repair Kit, model 50100 (Shinn Fu Company of America, Inc. (Kansas City, MO)) were used between the cylinder rod of the hydraulic cylinder and the pushing frame. Three extension tubes and at any given time, one or the other of two pushing feet of the kit, were used (Fig. 3.10). Each extension tube had a male and a female end, so the tubes could be assembled end-to-end. The rod of the hydraulic cylinder extended 25 mm beyond the face of the steel collar (Fig. 3.11). The female end of an extension tube slid over that protruding end of the cylinder rod and that face of the extension received force from the steel collar.

Shown in Fig. 3.11 is a lysimeter box on the guiding frame, at the start of pushing the box into the soil wall. At the start of pushing a box, the longest extension or assembly of multiple extensions that would fit between the retracted hydraulic cylinder and the pushing frame, was used. When the hydraulic cylinder reached its fully extended position, the rod was then retracted and a longer extension or assembly of multiple extensions that would fit was used, and this process was repeated until the combination of the pushing box and lysimeter box had reached their desired locations in the soil.

When the trailing edge of the lysimeter box had nearly reached the soil wall, a pushing box (Fig. 3.12) was placed on the guiding frame (Fig. 3.13) and was used for pushing the lysimeter box further into the soil, to its final position. The height and width (Fig. 3.5) of the

pushing box matched those of the corresponding lysimeter box and the length, L (Fig. 3.5), of the pushing box for the pan lysimeter was 395 mm, and for the wick lysimeter was 420 mm. Unlike the lysimeter boxes, the pushing boxes did not have removable lids. The fixed and pivoting tabs on the leading edge of the pushing box (Fig. 3.12) and two pivoting tabs on the trailing edge of the lid of the lysimeter box (Fig. A1) maintained alignment of the pushing box with the lysimeter box. This alignment was important in providing structural strength of the boxes as they were pushed into the soil.

When we used the guiding frame for pushing the steel boxes into the soil, the hydraulic oil pressure in the cylinder was typically 2800 to 6200 kPa, which correspond to pushing forces of 22 to 50 kN. The maximum oil pressure we observed in the cylinder was 13 MPa which corresponded to a pushing force of 106 kN. This occurred while pushing only one pair of the total of 18 pairs of steel boxes used in the project. When this large force occurred, the force caused the steel in part of the pushing box to yield. The relatively high soil bulk density (Table 3.1) contributed to these relatively large pushing forces. This 106 kN force exceeds the advertised 89 kN force capacity of the extension tubes, and is not recommended.

Before some of the lysimeter boxes were inserted in the soil, we used an Irwin Speedbor 25 mm diameter ship auger bit (Irwin Industrial Tools, Huntersville, NC) that was 300 mm in length, powered by a cordless handheld electric drill to drill six holes in the wall of soil. The holes were drilled in the direction parallel to the box sliding direction, in a three-column by two-row pattern, with each hole being about 30 mm inboard of where the lysimeter box would penetrate the wall. The holes were drilled in an attempt to make it easier for the soil to move inward, away from the walls of the box, as the box penetrated the soil, to reduce the force needed

for pushing the box into the soil. Drilling these holes in the soil seemed to make it somewhat easier for the box to penetrate the soil.

Before pushing one of the steel lysimeter boxes into the soil, we used a grinder to bevel the leading edge of the box, to see if this would improve penetration of the box into the soil. Pushing this box into the soil was somewhat easier, compared to the other lysimeter boxes which had blunt, non-beveled edges.

After the two steel boxes for each lysimeter were pushed into the soil, the guiding frame was removed from the soil pit. We then used shovels, trowels, and a handheld rototiller to remove the soil from within each pair of steel boxes (Fig. 3.14). The rototiller was a handheld Troy-Bilt Horse™ TB525CS attachment-capable trimmer (MTD Products Inc., Cleveland, OH) with a 29 cc, 4-cycle engine, equipped with a rotary tiller attachment mounted to this attachment-capable trimmer. The rotary tiller attachment was a TrimmerPlus GC720r Add-On Garden Cultivator (MTD Southwest, Inc., Tempe, AZ) and had four six-tooth tine pieces, each 200 mm in diameter. The soil within the steel boxes had a relatively high bulk density and was difficult to penetrate with a shovel, so one of the most difficult parts of this project was removing the soil from the steel boxes. The rototiller made this procedure considerably easier.

When the rototiller was used, its gasoline engine and the human operator were in the soil pit. For safety, it is important to avoid having excessive engine exhaust fumes within the pit, so an electric fan blowing fresh air down into the soil pit may be helpful. Four-cycle engines typically have lower emissions than 2-cycle engines, so a 4-cycle engine is expected to be better than a 2-cycle engine.

The soil at the upper surface of the tunnel, that was revealed when the lid of the lysimeter box was removed, was the soil surface against which the top of the lysimeter was placed. After removing the lid and before inserting the lysimeter in the tunnel, we used a wire brush to slightly roughen that horizontal soil surface to undo any smearing of that surface that may have occurred when the steel boxes slid against that soil. Any smearing of that soil may have caused macropores in the soil to become blocked, so we used this wire brushing to attempt to restore the status of the macropores to its original condition.

When the lysimeter box was in its installed position in the soil, the lysimeter was positioned within the box so the upper surface of the lysimeter was approximately centered within the exposed horizontal soil surface at the upper surface of the tunnel (Fig. 3.15). Therefore, the horizontal gaps between the perimeter of the stainless steel frame at the upper surface of the pan lysimeter and the edges of the opening provided by the steel boxes were about 15 mm. Similarly, the horizontal gaps between the edges of the wick lysimeter and the edges of the opening provided by the steel boxes were about 15 mm.

3.3 CONCLUSION

This equipment and method for installing pan and wick lysimeters was developed at the USDA-ARS National Soil Dynamics Laboratory and Biosystems Engineering Department, Auburn University. The installation process was done providing minimal disturbance to the soil. The walls of the box held the soil of the ceiling in the tunnel in its place after removing the lid of the lysimeter box.

Table 3.1. Mean soil dry bulk density and soil water content in pit walls when steel boxes for lysimeters were installed.

Depth beneath soil surface (mm) ^[a]	Soil dry bulk density (Mg/m ³)	Soil water content (% d.b.)
500 - 570	1.57	11.7
565 - 635	1.49	15.7
690 - 760	1.56	14.5

^[a] **Depths of upper edges of steel boxes were 500 mm for both the pan and wick lysimeters. Depths of lower edges were 760 mm for the pan and 730 mm for the wick lysimeters.**



(a)



(b)

Fig 3.1. (a) Zero-tension pan lysimeter. Black beads are polypropylene beads.

Dimensions of the upper surface of the bead portion of the lysimeter are 280

mm x 430 mm. (b) Wick lysimeter. Dimensions of the horizontal Plexiglas

thermoplastic piece beneath the wick material are 300 mm x 300 mm.

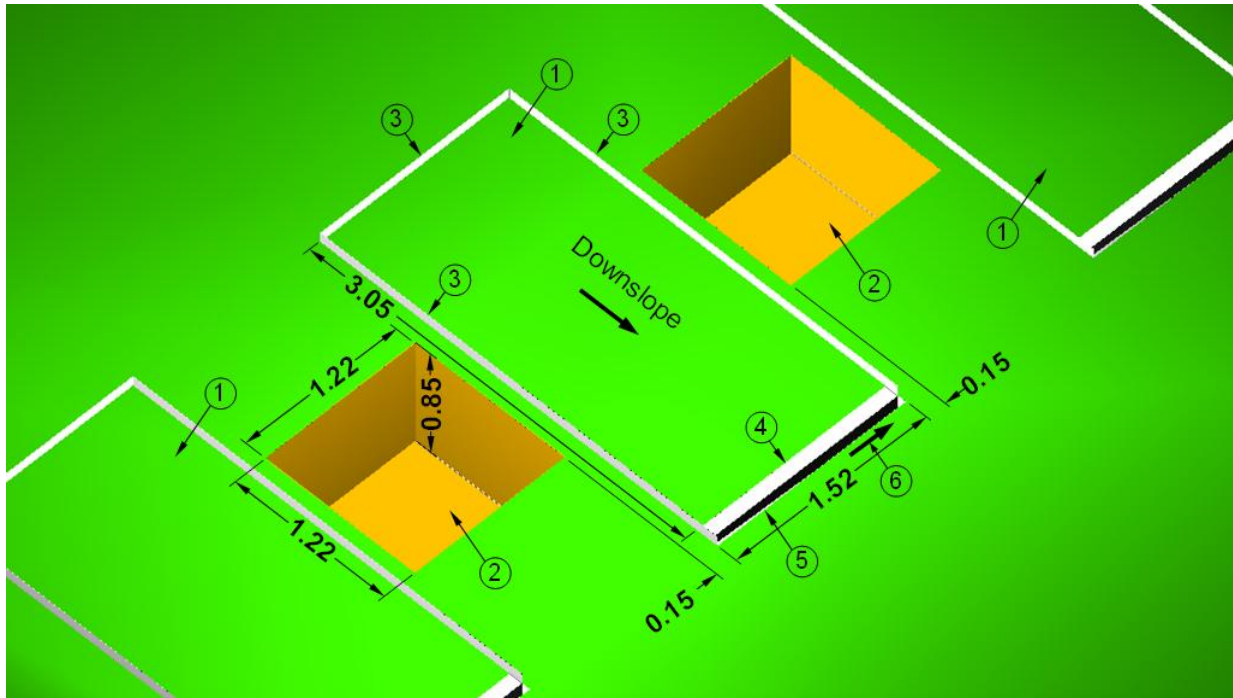


Fig 3.2. Layout of plots and soil pits: (1) one plot, (2) pit in soil between two adjacent plots, (3) vertical sheet metal borders of plot, (4) sheet metal in same plane as soil surface (part of trough), (5) trough to catch plot runoff water, (6) direction of water flow in trough. Units of dimensions are m.

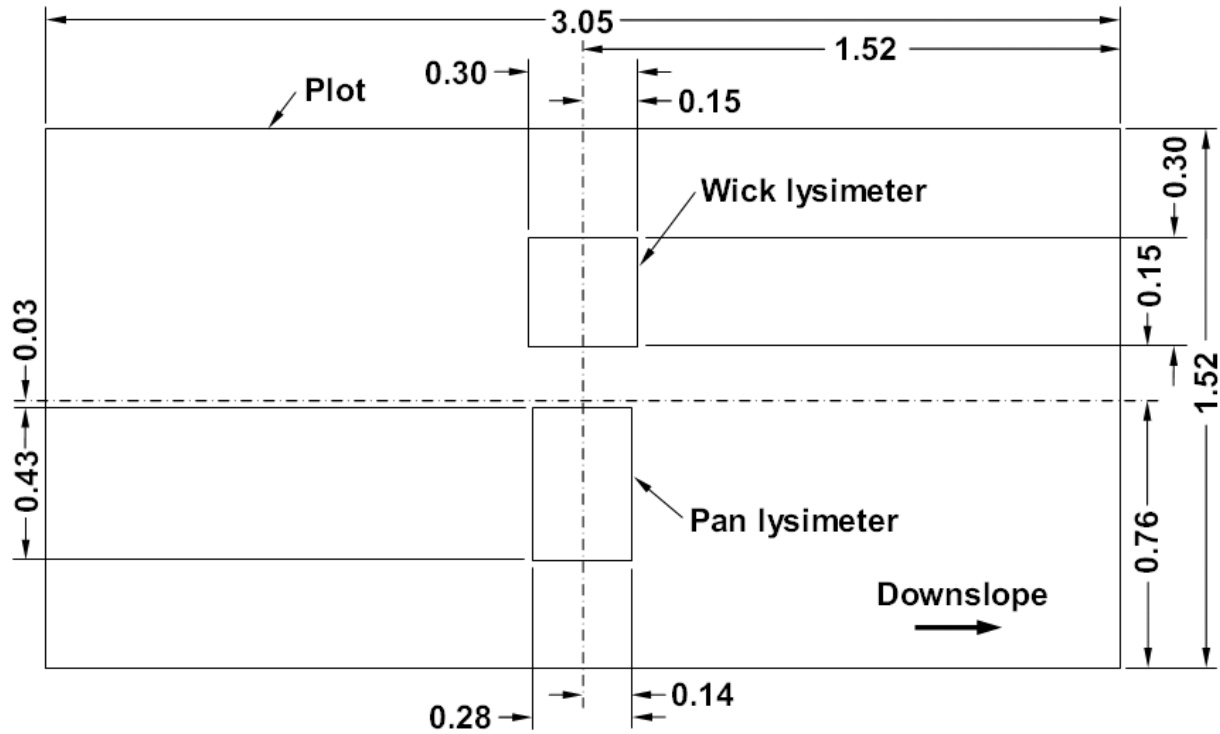


Fig 3.3. Top view of one plot, showing locations and dimensions of the wick and pan lysimeters. Pan lysimeter dimensions show the polypropylene bead portion of the lysimeter. Units of dimensions are m.

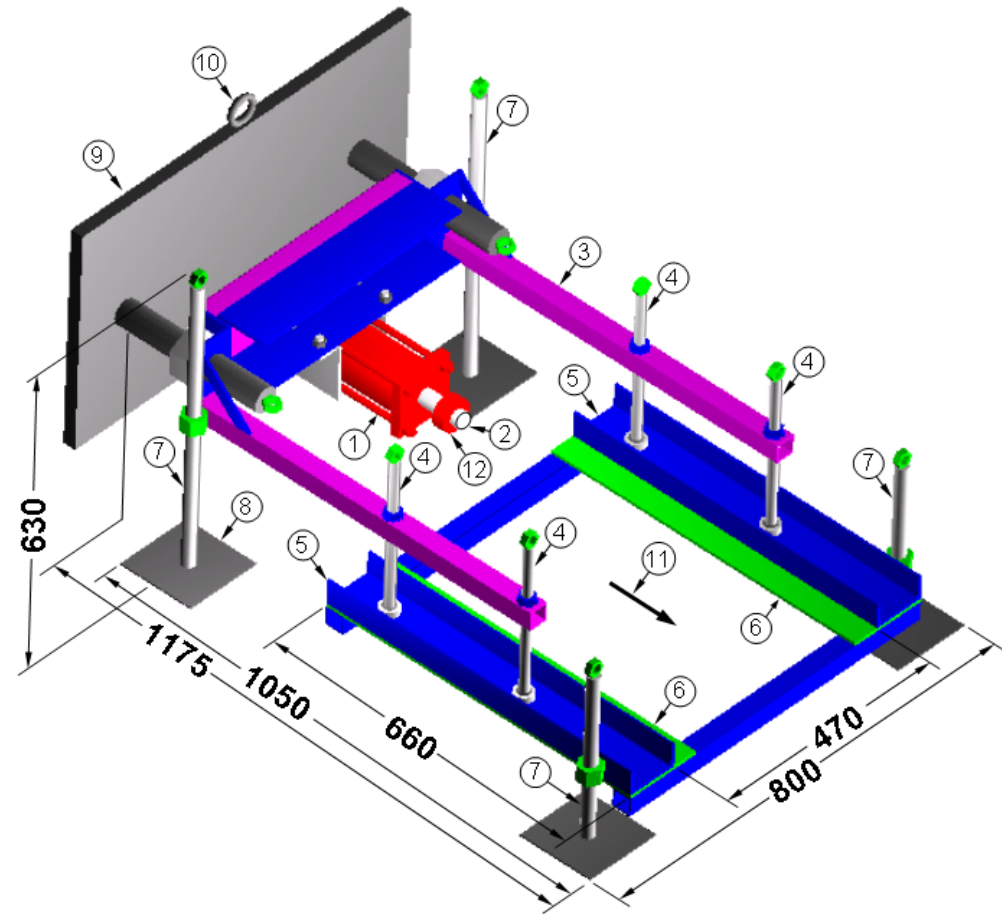


Fig 3.4. Guiding frame for pushing the steel boxes (not shown) horizontally, from a pit, into soil beneath a plot: (1) hydraulic cylinder, (2) cylinder rod of hydraulic cylinder, (3) square steel tube of upper frame section, (4) threaded rod for vertical adjustment of hydraulic cylinder relative to lower frame, (5) steel channel of lower frame, (6) steel bars on which steel boxes slid, (7) threaded rod for adjusting height of guiding frame, (8) base plate, (9) steel backstop plate (760 mm x 460 mm x 25 mm), (10) eyebolt for lifting steel backstop plate, (11) steel box sliding direction (horizontal, in the cross-slope direction), (12) steel collar on cylinder rod of hydraulic cylinder. Units of dimensions are mm.

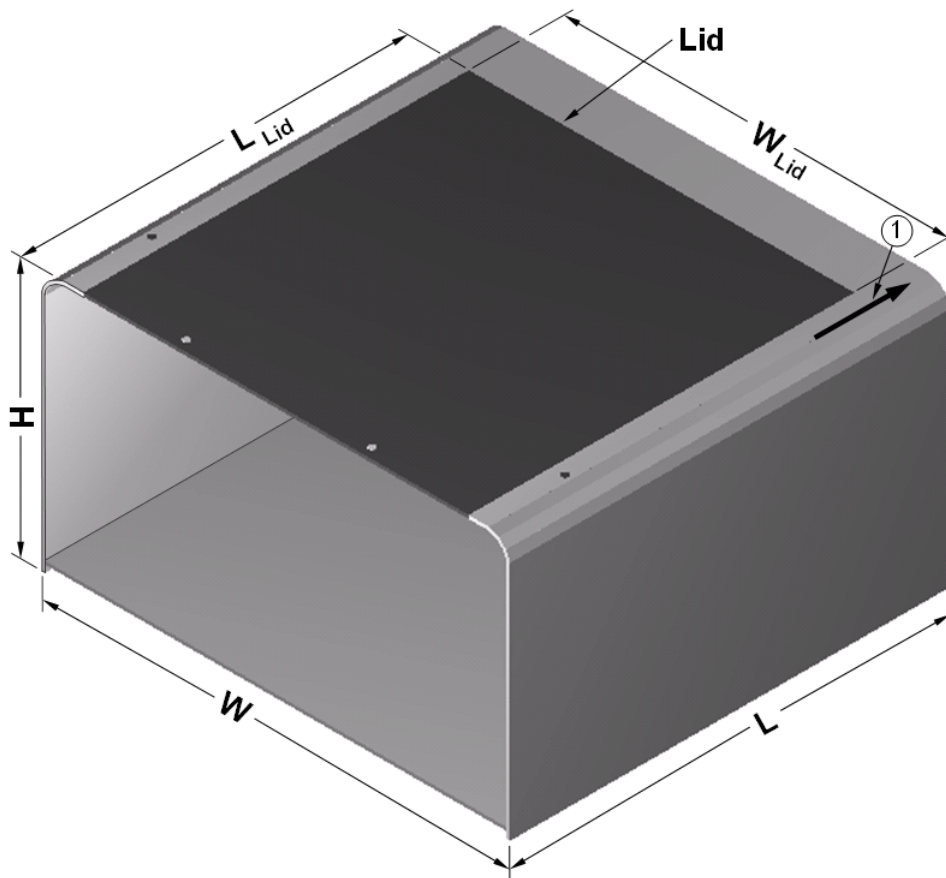


Fig 3.5. Lysimeter box constructed of 3 mm thick steel. Lid was removable, and was removed after the box was installed in soil beneath a plot: (1) sliding direction. For the pan lysimeter, the lysimeter box dimensions were $L = 585$ mm, $W = 470$ mm, $H = 260$ mm, $L_{Lid} = 510$ mm, and $W_{Lid} = 360$ mm. Lysimeter box dimensions for the wick lysimeter were $L = 405$ mm, $W = 430$ mm, $H = 230$ mm, and $L_{Lid} = W_{Lid} = 330$ mm.

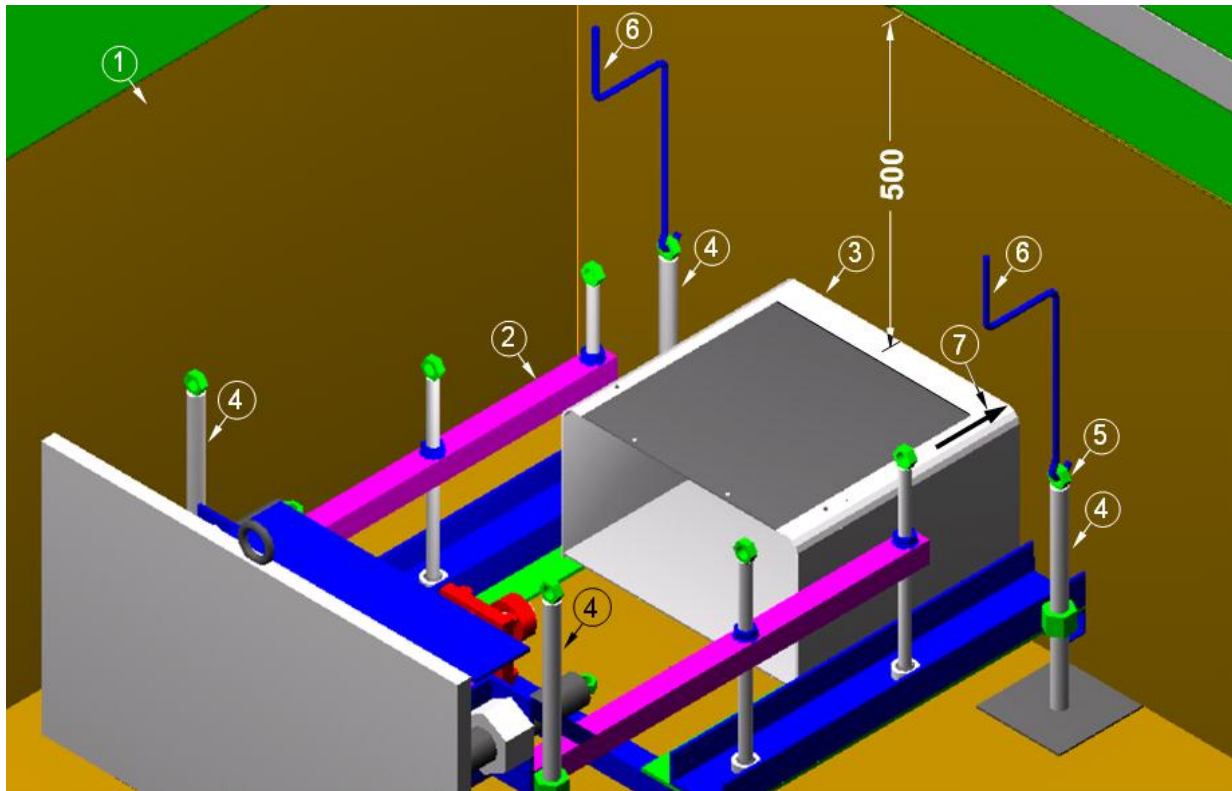


Fig 3.6. A lysimeter box on the guiding frame, before the box has penetrated the soil wall.

For clarity, two walls of the soil pit are not shown: (1) pit in soil, (2) guiding frame, (3) lysimeter box, (4) threaded rod for adjusting height of guiding frame, (5) hex nut welded to threaded rod, (6) crank handle from a scissors jack, for adjusting height of guiding frame, (7) sliding direction. Units of the dimensions are mm.



Fig 3.7. Soil pit between two plots, with guiding frame being used in the pit to push steel boxes into soil. Tractor hydraulics powered the hydraulic cylinder of the guiding frame.

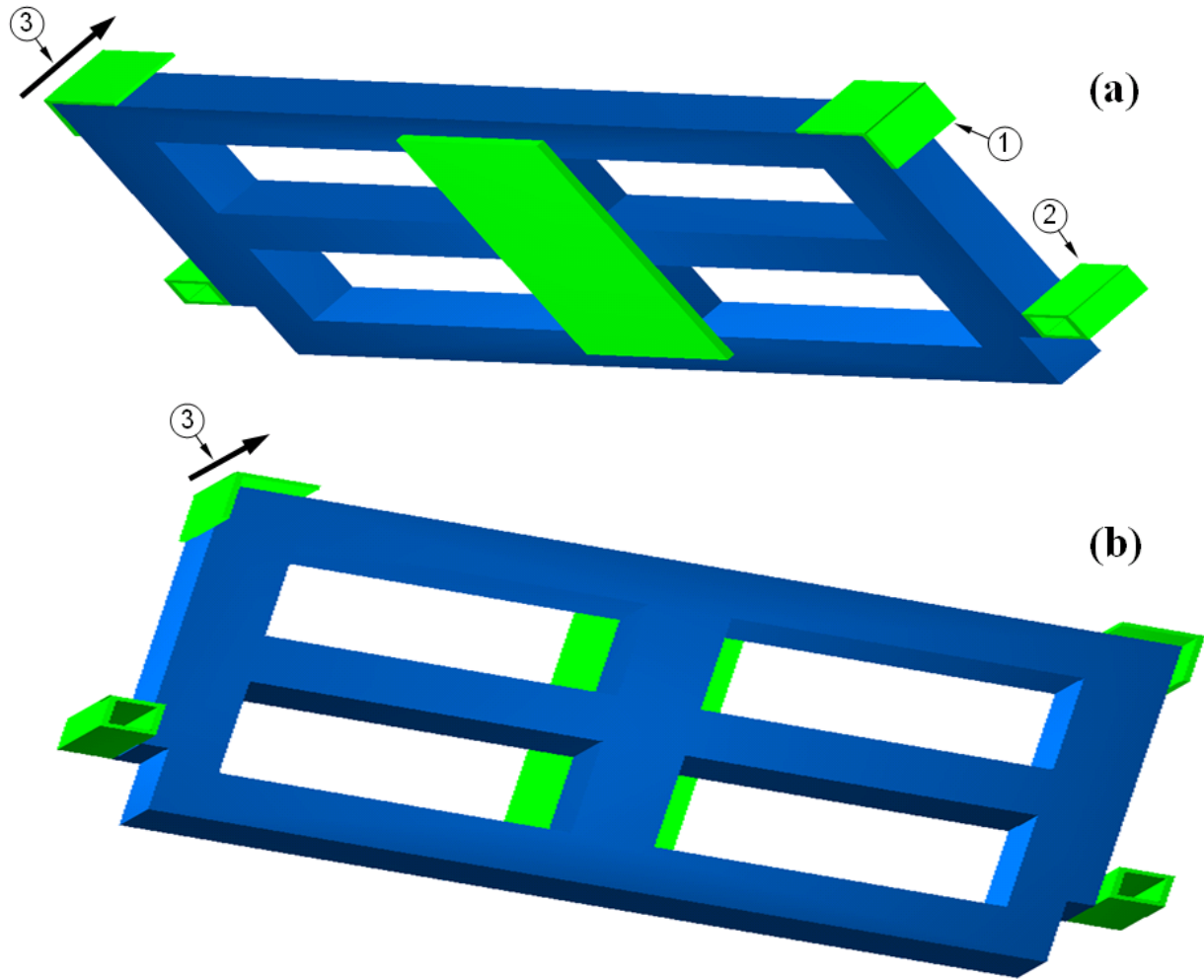


Fig 3.8. Pushing frame, for pushing on the trailing end of a lysimeter box or pushing box:
(a) view generally from trailing side of frame, and (b) view from leading side of
frame. (1) steel angle, (2) square steel tube, (3) sliding direction.

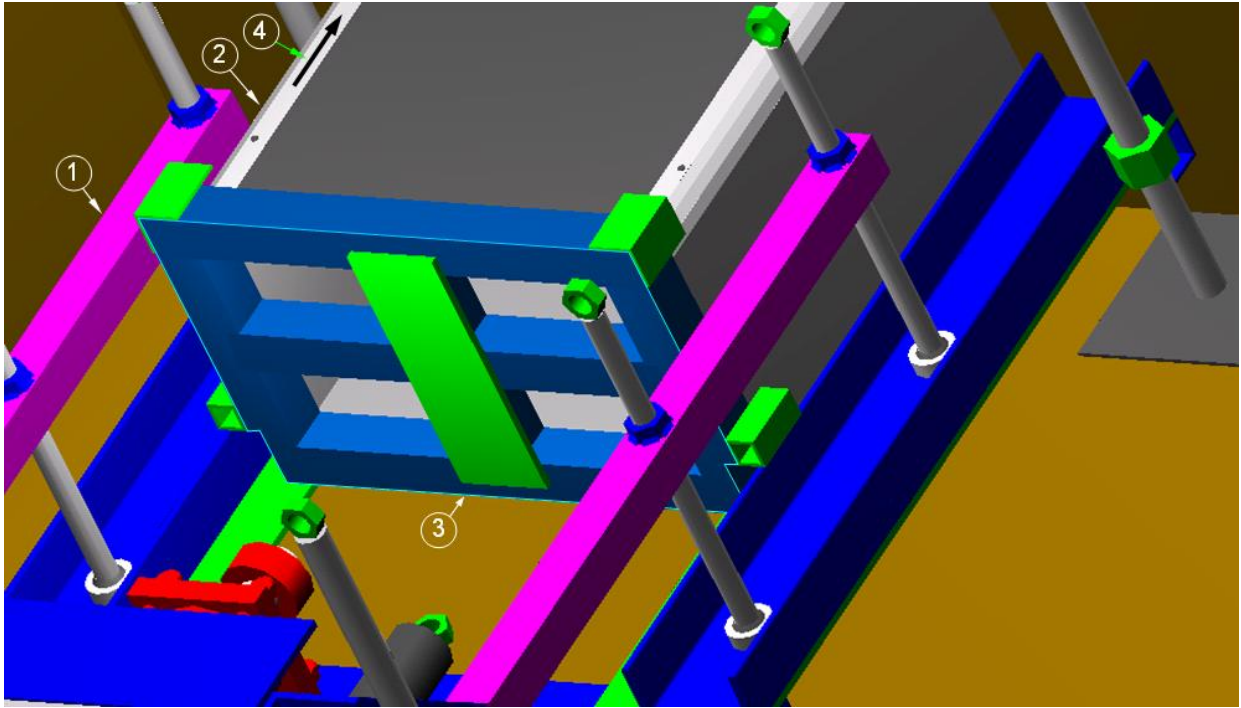


Fig 3.9. Pushing frame in place at the trailing end of a lysimeter box on the guiding frame, before the hydraulic cylinder has started pushing: (1) guiding frame, (2) lysimeter box, (3) pushing frame, (4) sliding direction.

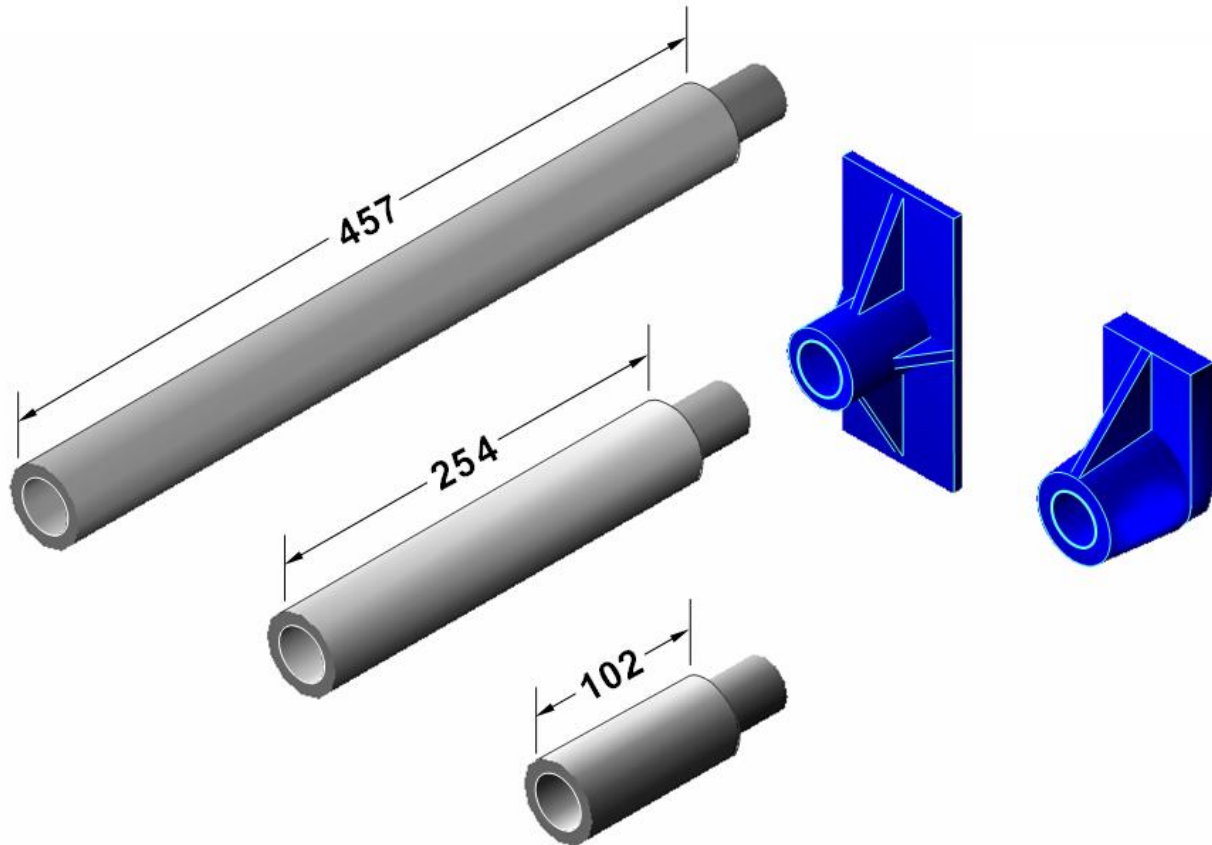


Fig 3.10. Three extension tubes (left) and two pushing feet that were used with the guiding frame. One of the pushing feet was slid onto the small diameter end of an extension tube. That pushing foot then pushed against the pushing frame as the female end of the extension tube was pushed by the steel collar on the cylinder rod of the hydraulic cylinder. Units of dimensions are mm.

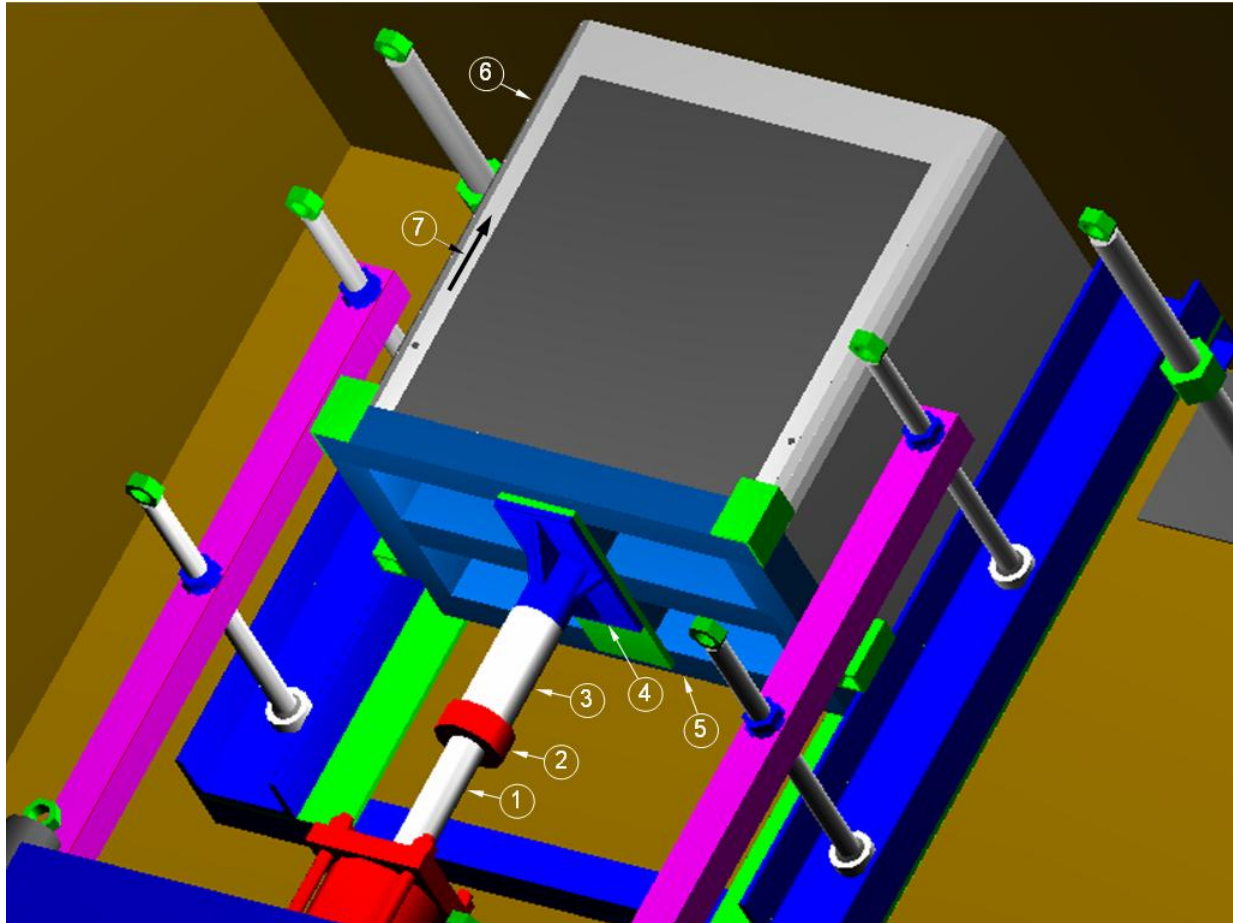


Fig 3.11. A lysimeter box on the guiding frame, before the box has penetrated the soil wall, while pushing is ready to begin: (1) cylinder rod of hydraulic cylinder, (2) steel collar on cylinder rod, (3) extension tube, (4) pushing foot, (5) pushing frame, (6) lysimeter box, (7) sliding direction.

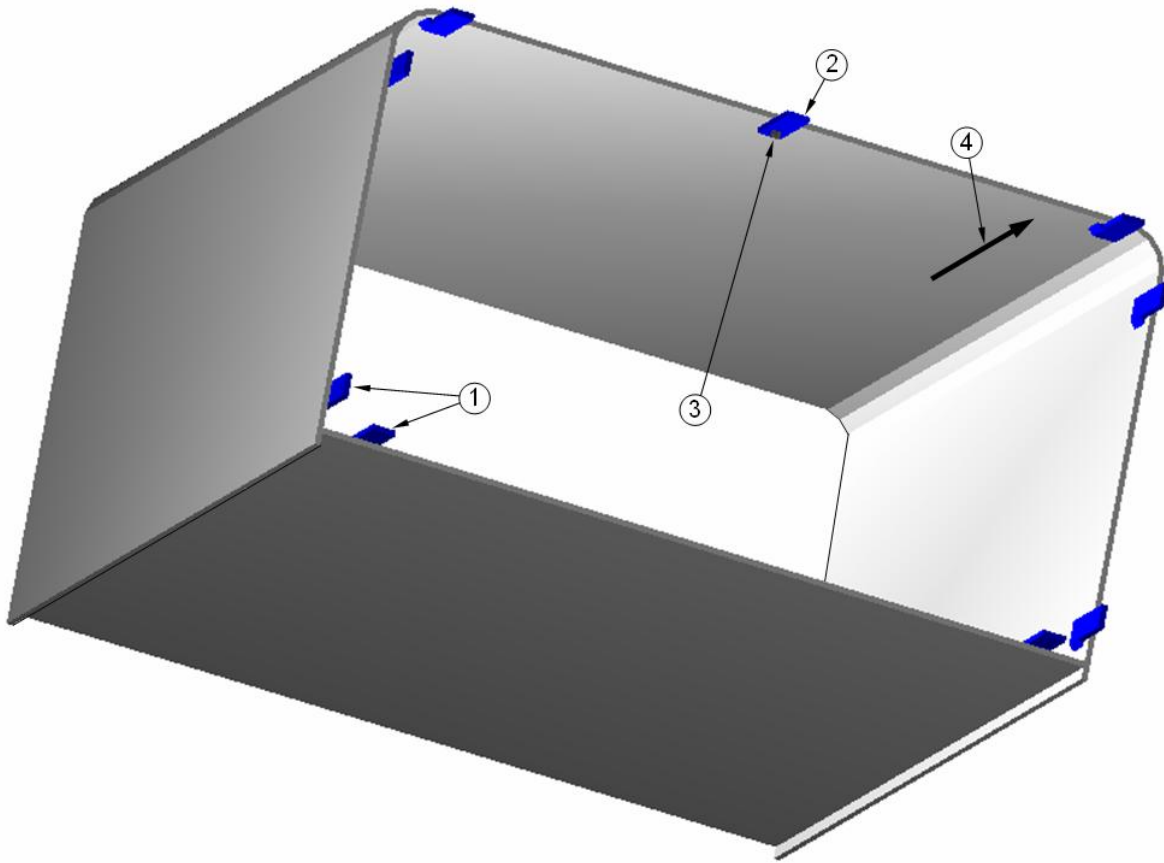


Fig 3.12. Pushing box constructed of 3 mm thick steel: (1) fixed tabs, (2) pivoting tab, (3) pop rivet for pivoting tab, (4) sliding direction.

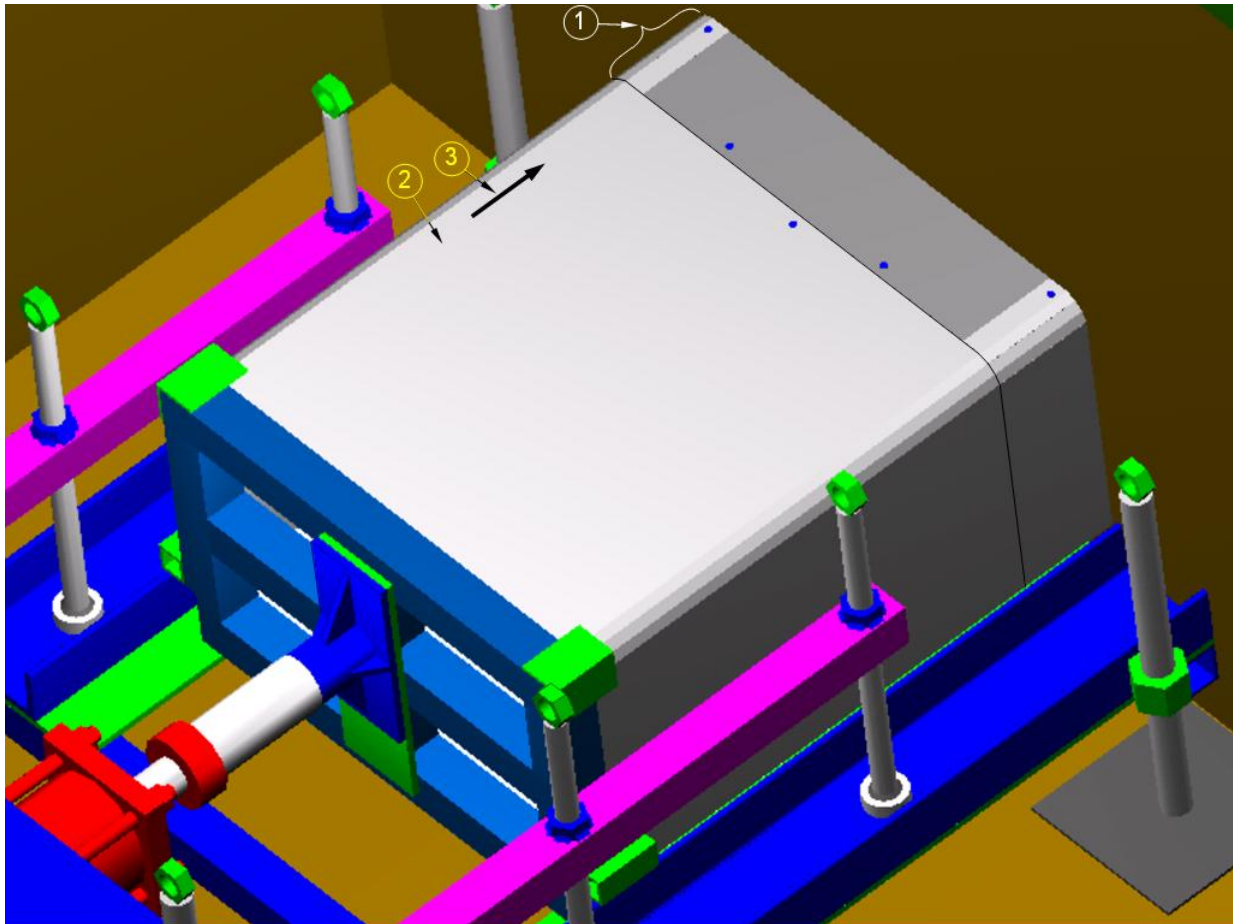


Fig 3.13. Lysimeter box and pushing box on guiding frame: (1) trailing end of lysimeter box (most of the length of the lysimeter box has already been pushed into the soil), (2) pushing box, (3) sliding direction.

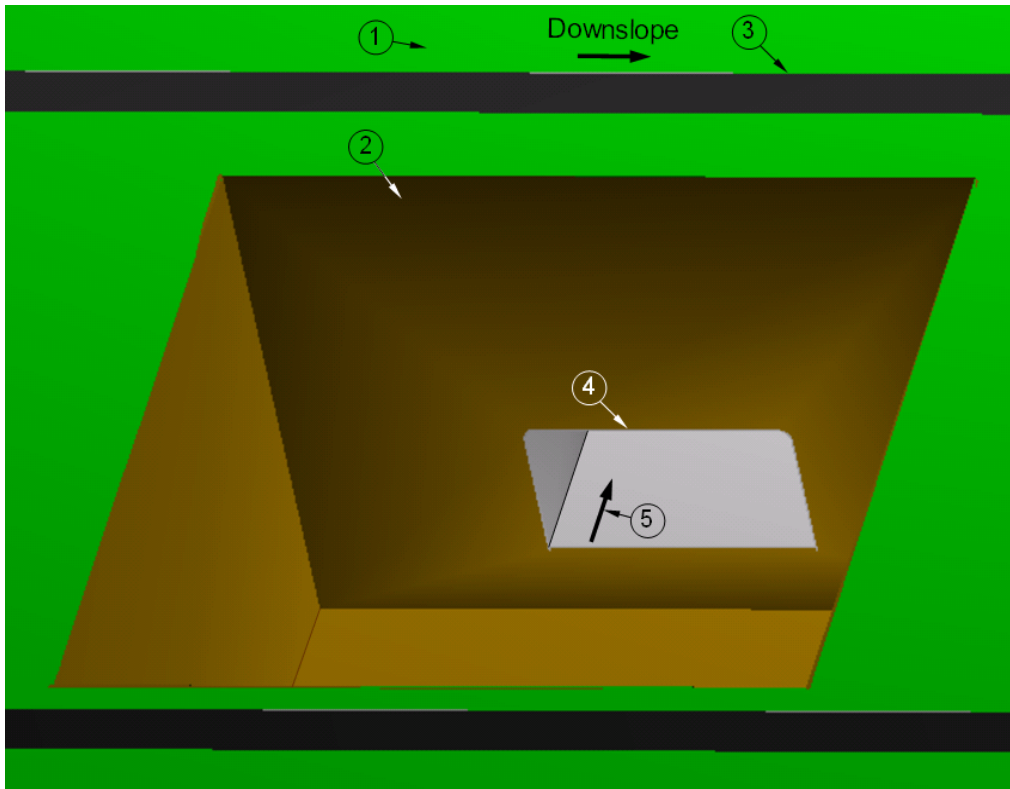


Fig 3.14. Tunnel after lysimeter box and pushing box have been inserted, and the soil removed from within the boxes: (1) one plot, (2) pit in soil between two adjacent plots, (3) vertical sheet metal border of plot, (4) pushing box and tunnel, (5) direction in which boxes were pushed into soil.

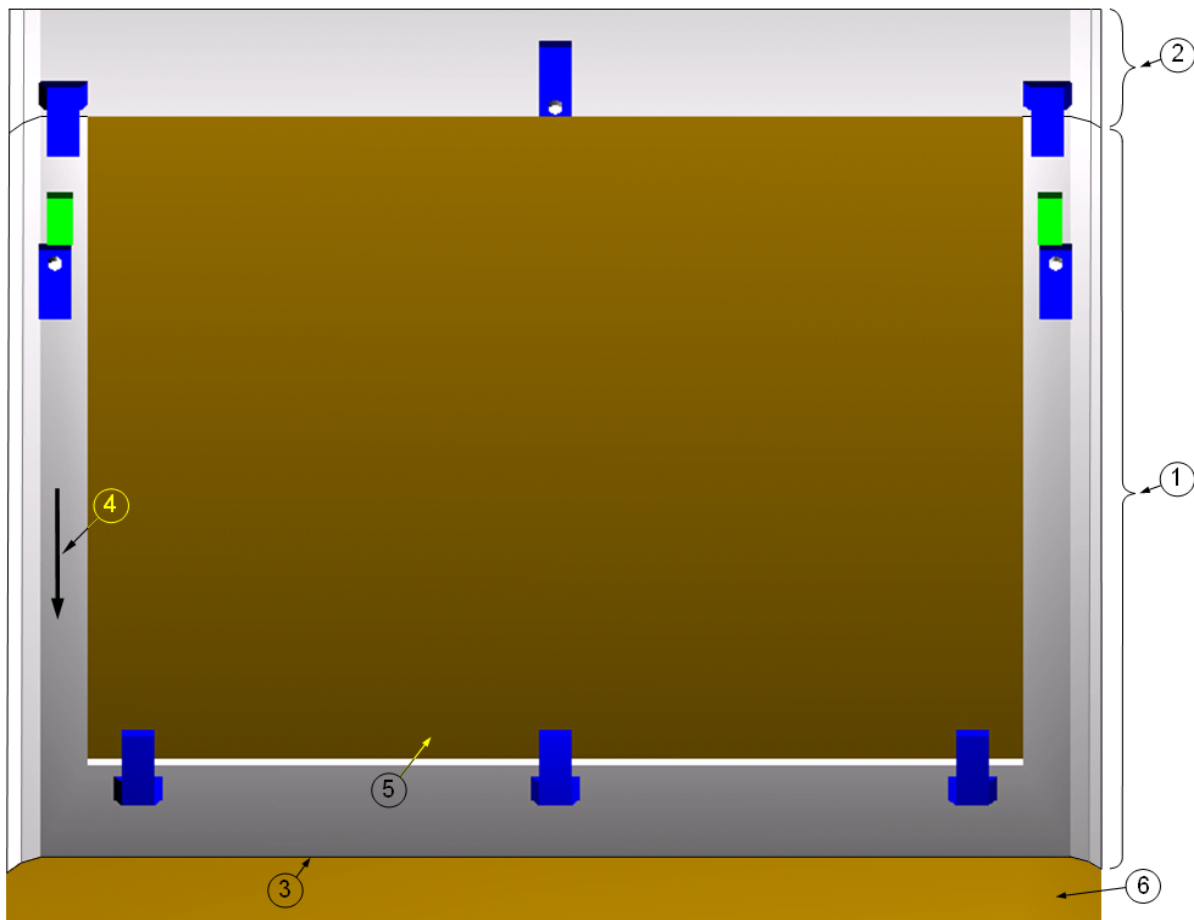


Fig 3.15. View from within lysimeter box after soil has been removed from within the lysimeter box and pushing box and after lid has been removed. View looking upward at soil at upper surface of tunnel: (1) lysimeter box, (2) pushing box, (3) leading edge of lysimeter box, (4) direction in which boxes were pushed into soil, (5) soil at upper surface of tunnel, (6) vertical wall of soil at end of tunnel.

CHAPTER 4

SURFACE AND SUBSURFACE TRANSPORT OF PHOSPHORUS FROM SURFACE-APPLIED AND SUBSURFACE-BANDED POULTRY LITTER

4.1 INTRODUCTION

Phosphorus (P) is one of the essential nutrients required for plant and livestock growth. However, P loss in agricultural runoff has received considerable attention due to non-point source (NPS) pollution caused by it. Phosphorus input to surface waters contributes to eutrophication and growth of toxic algae, and oxidation of organic matter reduces the dissolved oxygen levels below the respiration requirement of fish (Carpenter et al., 1998; Edward and Daniel, 1994). Although for the growth of aquatic biota nitrogen (N) and carbon (C) are also required, P is considered as the main limiting nutrient. This is because of difficulty in controlling N fixation by some blue green algae and air-water exchange of N and C. Agricultural runoff is considered as the one of the main source of NPS pollution of phosphorus (Carpenter et al., 1998).

The state of Alabama is among the top three states, along with Georgia and Arkansas, in broiler chicken production. Broiler production in Alabama results in generation of more than 1.25 million tons of poultry litter annually (Aksoy et al., 2008). Poultry litter average nutrient composition in Alabama is approximately equivalent to a 3-3-2 (N-P-K) grade fertilizer (Mitchell and Donald, 1995). Because of nutritive value and cheap alternative to fertilizer,

broiler litter is commonly applied to pastures to supply essential nutrients. Broiler litter application is confined to local areas of broiler production because of the expense of transporting litter (Sharpley et al., 1994; Moore et al., 1995). In Alabama, the major poultry litter producing counties (Marshall, Cullman, DeKalb, and Blount) are located in the Sand Mountain Region of north Alabama (Sen et al., 2008). The repeated long term application of poultry litter in this region has resulted in increase of soil P levels much greater than crop requirements (Kingery et al., 1994). In addition to the repeated application of poultry litter contributing to the buildup of P, there are other factors which contribute in increasing soil P level. For example, the application of poultry litter in the past was based mainly on the N requirement of crops. This results in increase of soil P level, as poultry litter has low N to P ratio than N to P ratio required by plants. Poultry litter average nutrient composition is equivalent to a 3-3-2 grade fertilizer and the nutrient requirement of fescue pasture is 9-7-1 (Mitchell, 1999), which means application of poultry litter on the N basis will supply extra P than removed by the plant. The loss of P from soil in surface runoff directly depends on soil P level. The greater the P level in soil, more is the P loss in surface runoff in sediment bound and dissolved forms (Sharpley, 1998). However as erosion rates from pastures and hay are low, surface runoff carries little sediment and dissolved phosphorus (DP) is the dominant form of P (Sharpley et al., 1998). Most of the DP is immediately available for biological uptake while sediment P is a long term source to aquatic biota (Sharpley, 1993).

The transfer of P from agricultural land can occur through surface or subsurface pathways. However, the capacity of most subsoils to fix inorganic P has meant that subsurface transfer has traditionally been perceived to be of minor importance (Baker et al., 1975; Burwell et al., 1977; Sharpley and Syers, 1979). However, now it has been realized that P transfer can

occur through subsurface flow at a level which can cause impairment of the water bodies (Turner and Haygarth, 2000; Sims et al., 1998). In areas where repeated application of manure takes place, the sorption capacity of soil profiles has become saturated to the extent that continuous, environmentally significant P loss via subsurface flow can occur (Sims et al., 1998). In organic soils and coarse textured mineral soils with high organic matter content P leaching has also been reported, because of low concentration of soil constituents like clays, oxides of iron (Fe) and aluminum (Al), and carbonate which are responsible for P retention (Sims et al., 1998). Kingery et al. (1994) also reported P leaching to a depth of approximately 60 cm in tall fescue (*Festuca arundinacea Schreb.*) pasture in the Sand Mountain region of north Alabama after long term (15-28 yr) application of poultry litter.

The P loss from fields depends upon different factors such as rate, method, and time of application of litter; and amount and time of rainfall after manure application (Sharpley et al., 1998). The method of poultry litter application plays an important role in surface runoff water quality. The most common method of poultry litter to pastures is the surface application, especially in the Sand Mountain region of north Alabama. However, during surface application of poultry litter some part of poultry litter falls on top a thatch layer, which prevents direct contact between poultry litter and soil (Brinson et al., 1994). This prevents immediate adsorption of P in poultry litter by soil, and results in P loss in surface runoff (Schroeder et al., 2004). Some previous studies have shown to reduce nutrient loss in surface runoff with subsurface application of poultry litter. For example, Sistani et al. (2009) showed that nutrient losses were reduced 10 times when broiler litter was applied in subsurface-bands, as opposed to surface broadcast application. Ross et al. (1979) found that injecting dairy manure into the soil reduced N and P losses in runoff. Nichols et al. (1994) showed that incorporating surface-

applied litter did not improve runoff water quality from fescue pasture because shallow rotary tillage method used by them damaged the grass thatch soil cover and did not adequately turn litter under soil surface. They suggested that nutrient loss in runoff might be reduced by using less disruptive method which moves poultry litter below the soil surface. Torbert et al. (2005) found that incorporation of poultry litter reduces the losses of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ in surface runoff of cultivated land. Incorporation by plowing followed by disking in a Barnes loam soil (fine-loamy, mixed Udic Haploboroll) resulted in P and N losses equal to those in surface runoff from unfertilized soil (Timmons et al., 1973). Pote et al. (2003) also showed that N and P concentration and mass losses reduced by more than 80% in runoff from incorporated litter than surface-applied broiler litter.

Many studies show that incorporating poultry litter in soil reduces P and other nutrient losses in surface runoff. But to our understanding, no study has been done to determine study the effect of subsurface application of poultry litter on quantity of P loss in subsurface flow. Therefore, objective of our study was to quantify P loss in surface and subsurface flow from surface and subsurface-banded poultry litter in the Sand Mountain region of north Alabama.

4.2 MATERIALS AND METHODS

4.2.1 Field Setup and Installation of Lysimeters

Nine plots of 3.05 m by 1.52 m plots were constructed at the Alabama Agricultural Experimentation Station's Sand Mountain Research and Extension Center at Crossville, AL on Hartsells (fine-loamy, siliceous, subactive, thermic, Typic Hapludults) soils. This type of soil is moderately deep (sandstone at 50-100 cm), well drained, moderately permeable, and is formed from acid sandstone (Sen et al., 2008). These soils are found on upper slopes of hills and

mountains and on level to moderately steep ridges. Out of nine plots, three plots were used as control (no litter), three plots for surface application of litter, and three plots for subsurface application of litter. Treatments were assigned in a randomized pattern to all plots. Surface application was carried out by manually broadcasting the poultry litter uniformly over the entire plot. For subsurface application of broiler litter, a subsurface band applicator was used (Fig. 4.1). This applicator was developed by the USDA-ARS National Soil Dynamics Laboratory (Auburn, AL). Using this applicator, on each plot, starting at the center of the plots, nine subsurface band trenches about 5 cm deep and 4 cm width extending across the width of the plot were made. The trenches were spaced at an interval of 30.5 cm on centers and were covered with soil after litter application to prevent any direct any contact between surface runoff and poultry litter in trenches. The broiler litter application rate of 5.0 Mg ha⁻¹ was used for each surface and subsurface-banded litter plot. Each plot had a uniform slope of 4% along the long axis and was cross leveled. These plots were constructed on tall fescue (*Fescue Arundinacea Schreb.*) pasture that was mowed to the height of 10 cm before the experiment. Each plot had sheet metal borders (10 cm belowground and 10 cm above ground) to isolate runoff. A metal trough attached to 10 cm horizontal approach sheet metal was installed at the downslope end of the plot to collect surface runoff and convey it to a collection point at the corner of the plot.

For the second part of the objective of this study, i.e. to quantify nutrients loss in subsurface flow, different type of lysimeters are available which can be used, although all lysimeters have some limitation associated with them. Monolith Soil column weighing lysimeters are capable of monitoring percolate volume and solute concentration accurately, but are not commonly used due to high cost and maintenance (Zhu et al., 2002). Soil coring is another inexpensive method used for leachate collection, however this method has some

limitations associated with it. This method is destructive, labor intensive, and doesn't allow repeated sampling of same site (Brandi-Dohrn et al., 1996 and Barzegar et al., 2004). Suction cup lysimeter is also commonly used despite some disadvantages. This type of lysimeter has small contact area and requires a continuous source of vacuum for sample collection (Grossmann and Udluft, 1991). These lysimeters also often miss critical solute pulse and cannot measure macropore flow (Barzegar et al., 2004). Another type of lysimeters developed by Brye et al. (1999) called equilibrium tension lysimeters (ETLs) have also been commonly used. These lysimeters make use of heat dissipation sensors (HDS) to measure the soil-water matric potential adjacent to the lysimeters. These require a human operator to visit them 2-3 times per week and manually adjust ETL suction to match that of surrounding soil. These types of lysimeters are also prone to error due to fluctuations in soil-water matric potential that occur in between adjustments (Brye et al., 1999).

Zero tension pan and passive capillary fiberglass wick are other type of lysimeters which are less expensive to install, easier to maintain, and disturb the soil to less extent in comparison with monolith lysimeters during installation (Zhu et al., 2002). But there are also some limitations associated with these types of lysimeters. Zero tension lysimeters depend only on gravity to cause water movement through them (Brye et al., 1999). These types of lysimeters collect leachate only from macropore flow and when the soil above pan is saturated (Barbee and Brown, 1986 and Zhu et al., 2002). Therefore when the soil is unsaturated water flow away from zero tension lysimeter resulting in low leachate collection efficiency (Jemison and Fox, 1992). The advantage of these lysimeters is that these provide a good way to study the chemical composition of leachate (Jemison and Fox, 1992). The other types of lysimeter which are believed to have good collection efficiency than pan lysimeters are called passive capillary

fiberglass wick lysimeters (Zhu et al., 2002). Wick lysimeters use self priming wicks to produce a hanging water column to exert suction on the soil column, making it to draw water from unsaturated soil without any external application (Boll et al., 1992). However some previous work has shown effect of wick material on chemical composition of sample collected by it is not well known (Goynes et al., 2000). Therefore, combination of both pan and wick lysimeters can provide a good method to monitor the P loss from fields through subsurface flow.

A pair of pan and wick lysimeter was installed 50 cm below soil surface in each plot. Pan lysimeters used were rectangular (45 by 30 cm) in shape. These lysimeters were filled with polypropylene beads which helped in easy interception of drainage water and diversion it to the collection device (Fig. 4.2). The pan lysimeter was designed with a sloping pan bottom that allowed water to flow to one corner of the pan. From this corner an outflow port covered with polypropylene mesh drained water through polypropylene tubing to a 9.45 L carboy. The outflow port was covered with polypropylene mesh to prevent the polypropylene beads in the pan from going down through outflow port. The wick lysimeters constructed were 30 by 30 cm. The design of the wick lysimeter was adopted from Holder et al. (1991). It consisted of a Plexiglas plate with 3.2 cm diameter hole at center draining water through polypropylene tubing to a 9.45 L carboy (Fig. 4.3). Wicks used were 12.7 mm in diameter supplied by Pepperell Braiding Co. (East Pepperell, MA). Hydrophobic chemicals from wick material were removed by combusting them at 400 °C (Knutson et al., 1993). The Plexiglas plate surface was covered with the wick material to achieve 100% cover. Each of the lysimeters had four turnbuckles to adjust the height of the lysimeters to bring the upper surface of the lysimeters in contact with the tunnel ceiling. During preliminary tests we found out that these turnbuckles were difficult to reach with the lysimeter inside the tunnel. Therefore, instead of using the turnbuckles we

decided to use two scissor jacks per lysimeter which were easily accessible inside the tunnel using the long handled crank (Fig. 4.4).

Previous work by (Zhu et al., 2002; Jemison and Fox., 1992) showed that for the installation of lysimeters, pits are excavated with a backhoe followed by excavation of the lysimeter tunnels using the gasoline engine auger. Then these lysimeters were installed at a required distance from the edge of the pit. A steel strip is placed against the ceiling and supported with pressure treated lumber to prevent ceiling from collapsing. This method can cause much more soil disturbance during installation and it is difficult to get uniform soil surface in contact with lysimeter. So we decided to develop a new method to install the lysimeters which will disturb the soil to the minimal extent and provide uniform soil surface to come in contact with top of the lysimeters.

The procedure for installation of lysimeters consisted of building steel boxes which can be put into the soil using the tractor hydraulics. The box which was used to cut the soil first was called the lysimeter box and the box to push this lysimeter box in the soil was called the pushing box. The pit was excavated using a backhoe and the guiding frame was placed in the pit after leveling the soil in pit. The lysimeter box was placed on the guiding frame and the depth of the frame was adjusted using the adjustable legs provided on the guiding frame so that the top of the box was 50 cm below the soil surface. A tractor hydraulics powered double acting hydraulic cylinder fitted on the guiding frame was used to push the lysimeter box and pushing box in the soil. After pushing the lysimeter box completely into the soil, the pushing box was placed behind the trailing end of the lysimeter box and aligned with it using the tabs fixed on the pushing box. The pushing box was pushed in the soil until its trailing end reached the edge of the soil wall. After putting the boxes at the correct position, soil was excavated from within

these boxes and the lid of the lysimeter box was removed. The ceiling surface of the tunnel was rubbed with wire brush to remove smearing before lysimeter top surface was brought in contact with the soil surface. The lysimeter was placed inside the lysimeter box and was raised up using scissor jacks to touch the ceiling of the tunnel. Detailed installation procedure is described in Chapter 3.

A rainfall simulator with one TeeJet ½ HH-SS50WSQ nozzle manufactured by Spraying Systems Co., Wheaton, IL was used to conduct rainfall simulation. This nozzle was fixed at the center of the simulator which was 305 cm above the soil surface. The aluminum frame was fitted with tarps to provide a windscreen. The pressure gauge and water piping were mounted on the aluminum frame. To conduct experiment at same rainfall intensity, rainfall simulator was calibrated. Fifteen cylindrical cans which were about 101 mm in diameter were placed below rainfall simulator at different positions and rainfall simulation was conducted for 10 minutes. The volume collected by each cylindrical was measured. The same procedure was repeated at different pressures. At different pressures rainfall intensity was measured and 5 psi pressure was found out to be the pressure to conduct rainfall simulation at an intensity of 70 mm h⁻¹. During the experiment National Research Project for Simulated Rainfall – Surface Runoff Studies Protocol was followed (National Phosphorus Research Project, 2005). The rainfall simulation was conducted at an intensity of 70 mm h⁻¹ based on the 1 h, 10 year return period of that area. On an average it took about 40 minutes on each plot for the start of runoff. 1 L of runoff samples were collected every 5 min for 1 h, 2.5 min after the start of runoff (Fig. 4.5). Flow rate was estimated by recording the time to fill 1 L of sample. Total runoff volume was also collected in a large bucket from each plot. Leachate samples from the carboys were collected at the end of rainfall event (Fig. 4.6). Immediately after runoff and leachate sample collection, samples were

stored at 4 °C until analyzed. Samples of water used for the rainfall simulation were also collected and analyzed before the experiment. All the water samples results discussed later on represent mean of three replications (3 Plots).

Before application of broiler litter three baseline soil samples were collected at five different depths i.e.0-5, 5-15, 15-25, 25-40, and 40-50 cm for each plot were collected using 2” bucket auger soil sampler outside the plot. The nutrient concentration of the top 0-5 cm layer is shown in Table. 4.1. The results of the soil P level at five different depths were used to show the overall P budget during this experiment discussed below. All the soil samples before the experiment were collected outside the plots i.e. 2-3 cm outside the sheet metal borders so that hydrology of the area inside the plot is not disturbed. The soil samples were analyzed for pH, moisture content, Mehlich 1 extractable P (M1-P), water extractable P (WEP), total Kjeldahl N (TKN), ammonium N (NH₄-N), and nitrate N (NO₃-N) (Table 1). Broiler litter used for the experiment was collected from a local broiler house. Samples of broiler litter were taken before its application to the plots and stored in a plastic bag at 4⁰C until analyzed. These samples were analyzed for water content, pH, electrical conductivity (EC), TN, TP, NH₄-N, NO₃-N, and PO₄-P (Table 2). The methods used to analyze soil and broiler litter samples are described below.

4.2.2 Chemical Analysis of Soil, Litter, and Water Samples

The runoff, leachate, soil, and broiler litter samples collected were analyzed for different nutrients at Auburn University, Agronomy and Soils Department, Nitrogen Laboratory. Water quality samples filtered by 0.45 µm filter were analyzed for NH₄-N, NO₃-N, and PO₄-P, while unfiltered samples were analyzed for TP. NH₄-N and NO₃-N were measured on filtered samples using a microplate procedure (Sims et al., 1995). A colorimetric method was used to measure

PO₄-P (Murphy and Riley 1962). To analyze TP, a 25 mL unfiltered water sample was digested with 10 mL of wet ash acid mix (70:30 nitric:perchloric acid) (John, 1972) prior to analysis via inductively coupled argon plasma (ICAP) spectroscopy (Spectro Ciros CCd, Side on Plasma, Germany).

For analysis of soil samples, soils samples were dried at 60 °C for 48 h and sieved through 2 mm sieve before analyzing them for different nutrients. NH₄-N and NO₃-N were extracted by taking 5 g of soil sample using 2 M KCl (Keeney and Nelson, 1982) and were then analyzed using a microplate procedure (Sims et al., 1995). To analyze WEP, 2 g soil was taken into a 40 mL centrifuge tube and extracting with 20 mL of distilled water for 1 h on a mechanical shaker (Self-Davis et al., 2000). After each sample was centrifuged, aliquots were filtered through a 0.45 µm membrane and acidified to pH 2 with HCl. After this WEP was determined colorimetrically (Murphy and Riley., 1962). For M1-P measurement, 5 g of sample was extracted with 20 mL dilute double acid mix of 0.05 N HCl and 0.025 N H₂SO₄ (Hue and Evans, 1986) prior to analyses via ICAP spectroscopy. For analysis of NH₄-N and NO₃-N in broiler litter, similar method was used as for soil samples, except instead of taking 5 g, 1 g of finely ground (1 mm mesh) poultry litter sample was taken. TP in litter was determined by dry ashing method (Hue and Evans., 1986). In this 0.5 g poultry litter was heated in a muffle furnace at 450°C for 4 h. This was followed by addition of 10 mL of 1 N HNO₃, evaporate to dryness and adding 10 mL of 1 N HCl to dissolve the residue. Broiler litter and soil samples were analyzed for organic C and Total N by dry combustion method (LECO TruSpec CN, LECO Corp., St. Joseph, MI). Measurements of pH were taken for soil (1:1 soil:water), broiler litter (1:3 litter:water) using pH meter (Denver instrument UB-5 Arvada, CO).

Statistical Analysis System (SAS Institute, 1999) was used to perform ANOVA using PROC GLM procedure. To separate out means of experimental results least significant method (LSD) method was used. Unless otherwise noted, all the statistical tests were performed at $\alpha = 0.05$ significant level.

4.3 RESULTS AND DISCUSSION

4.3.1 Water Budget

The water budget of the entire experiment is shown in Table 4.3. A rainfall simulator was used to apply rainfall immediately after litter application. In the case of subsurface-banded litter plots, about 6.8% of the rainfall contributed to 1 h of surface runoff, which was less than the amount of rainfall which contributed to 1 h of surface runoff in control and surface-applied litter plots. The reason for this can be that some amount of water was absorbed by broiler litter and some of it stayed in the trenches where broiler litter was applied. Since some volume of water stayed in the trenches, the percentage of rainfall which contributed to leachate was also less in these plots in comparison with the other plots. In these plots only 46.55% of rainfall contributed to leachate. This is not surprising as the subsurface applicator used to make trenches for subsurface application of broiler litter might have caused compaction of the soil and closed the macropores in the trenches, which prevented the water from moving down in the soil profile. Since control plots were without any broiler litter and trenches in them, percentage of rainfall which contributed to runoff and leachate was greater in these plots in comparison with surface and subsurface-banded litter plots. In control plots percentage of rainfall which contributed to 1 h of surface runoff and leachate was 8.9 and 69.64%, respectively. In surface-applied litter plots, the percentage of rainfall that contributed to runoff and leachate was between control and

subsurface-banded litter plots. In surface-applied litter plots the percentage of rainfall which contributed to 1 h of surface runoff and leachate was 7.8 and 64.7%, respectively. This is not surprising as these plots were without trenches which made the percentage of rainfall contributing to rainfall and leachate to be more than subsurface-banded litter plots. Since these plots were with broiler litter in them the percentage of rainfall which contributed to rainfall and leachate was less than control plots. Although there were differences in volume of rainfall and leachate among different plots, however these differences were not significant ($\alpha = 0.05$). In all the plots, less than 10% of rainfall contributed to surface runoff irrespective of the treatment. This result supports the previous study by Sen et al. (2009) that in this region less than 10% of the rainfall contributes to surface runoff. Also, showing that there is significant subsurface flow occurring in this region.

4.3.2 RUNOFF AND LEACHATE CONCENTRATION

4.3.2.1 Runoff Concentration

Nutrient concentrations in surface runoff are defined as the flow weighted nutrient concentrations, i.e., amount of nutrient loss in 1 h of runoff divided by total volume of runoff in a given time. The mean flow-weighted concentrations of the nutrients analyzed in runoff from different plots differ among different plots (Table 4.4). The method of litter application played an important role in surface runoff quality. Nutrient concentrations were significantly higher ($\alpha = 0.05$) in surface runoff of surface-applied litter plots in comparison with control and subsurface-banded litter plots. The nutrient concentrations of all the nutrients in subsurface-banded litter plots were very close to that of control plots. In fact there was no significant difference ($\alpha = 0.05$) found in nutrient concentration between control and subsurface-banded litter plots. The nutrient concentration results show that subsurface application of litter proved to

be better method to control nutrient concentration in surface runoff in comparison with surface application of litter. Detailed discussion on affect of litter application method on nutrient concentration in surface runoff is mentioned in chapter 3

The standard deviation was more in nutrient concentration from plots with surface-applied litter in comparison with control and subsurface-banded litter and it also followed the similar trend to concentration (Table 4.4). The possible variation in concentration from surface-applied plots might be presence or absence of broiler litter coming from surface-applied litter in runoff. In some samples even if small amount of broiler litter gets in, it can increase the amount of concentration by much more amounts in comparison with samples without or less broiler litter in them. In case of control and subsurface-banded there was less standard deviation. This might be because, in case of these plots most of the concentration was due to nutrient loss from top layer of soil which didn't have much variation in initial soil P content.

4.3.2.2 Leachate Concentration

The concentrations of nutrients in leachate were also affected by broiler litter application method (Table 4.5). Similar to runoff concentration, in leachate concentration also, subsurface application of litter proved to be a better method to reduce nutrient concentration in comparison with surface application of litter. The subsurface band applicator used for subsurface application of broiler litter might have compacted the soil in the trenches. This compaction would have closed the macropores in the soil, which would have prevented the nutrients from going down in the soil profile. The concentration of $\text{PO}_4\text{-P}$ and TP reduced by 95 and 37%, respectively, when the broiler litter was applied in the subsurface. Though there was no significant difference found in the concentration of TP between surface and subsurface-banded litter plots, the concentration

of $\text{PO}_4\text{-P}$ was significantly higher in leachate of surface-applied litter plots. Concentration of $\text{PO}_4\text{-P}$ and TP in leachate of control plots was significantly less in comparison with concentration of $\text{PO}_4\text{-P}$ and TP in leachate of surface and subsurface-banded litter plots. Although subsurface application of litter helped to reduce TP and $\text{PO}_4\text{-P}$ concentration in leachate, these concentrations were above the concentrations which can cause eutrophication. Foy and Withers (1995) showed that P concentration of only a few tens of $\mu\text{g L}^{-1}$ can cause eutrophication. In our case the concentration of $\text{PO}_4\text{-P}$ and TP was above 0.05 and 0.83 mg L^{-1} , respectively, in all the plots. The $\text{NO}_3\text{-N}$ concentration also reduced by 43% when broiler litter was subsurface-banded. There was no reduction in $\text{NH}_4\text{-N}$ concentration in leachate of subsurface-banded litter plots. However, no significant difference was found in leachate concentration of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ between surface and subsurface-banded litter plots. The concentrations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in leachate of surface and subsurface-banded litter plots were significantly higher than their corresponding concentrations in control plots. Similar trend in standard deviation was seen in the leachate concentrations as was seen in the runoff concentration (Table 4.5).

The concentration of $\text{PO}_4\text{-P}$ and TP was higher in surface runoff than subsurface flow (Fig. 4.7 & 4.8). This might be because surface runoff had more interaction with broiler litter, and in case of leachate some amount of nutrient might have stayed in the soil profile. In surface-applied litter plots, $\text{PO}_4\text{-P}$ and TP concentrations were about 65 and 78%, respectively, more in surface runoff than leachate. In case of plots with subsurface-banded litter, similar trend was observed. $\text{PO}_4\text{-P}$ and TP concentrations were 88 and 18%, respectively, more in surface runoff than leachate. In case of control plots also, $\text{PO}_4\text{-P}$ and TP concentration reduced by 81 and 75%, respectively, in leachate in comparison with their corresponding concentration in surface runoff. The other reason which might have resulted in increase in concentrations at surface runoff is

more soil P level in top few cms of soil and it decreases with increase in depth (Detailed in Chapter 2; Kingery et al., 1994).

4.3.3 RUNOFF AND LEACHATE MASS LOSS

4.3.3.1 Runoff Mass Loss

Mass loss (loading) in runoff was determined by taking the product of concentration of each discrete sample and corresponding flow volume and then summing up these incremental mass losses for the entire runoff duration. The mean loading of runoff constituents i.e. TP, PO₄-P, NH₄-N, and NO₃-N followed the similar trend to concentration (Fig. 4.9 & 4.10). Significantly ($\alpha = 0.05$) greater loading of the nutrients (TP, PO₄-P, NH₄-N, and NO₃-N) in runoff were observed from surface-applied litter plots than subsurface-banded. There was no significant difference ($\alpha = 0.05$) found in loading of TP, PO₄-P, NO₃-N, and NH₄ between control and subsurface-banded litter plots. Detailed discussion on mass loss of nutrient in surface runoff is discussed in Chapter 3. Similar trend in standard deviation was seen in the surface runoff loading as was seen in the surface runoff concentration (Fig. 4.9 & 4.10).

4.3.3.2 Leachate Mass Loss

The loading in leachate was determined by taking the product of concentration of nutrient in leachate and the total volume of the leachate collected. Similar trend to leachate concentration was seen in the loading (Fig. 4.11 & 4.12). The loading of PO₄-P and TP was reduced by 97 and 47%, respectively, in leachate when broiler litter was subsurface-banded. PO₄-P loading in leachate from surface-applied litter plots was significantly higher ($\alpha = 0.05$) than PO₄-P loading from control and subsurface-banded litter plots. There was no significant difference ($\alpha = 0.05$) found in PO₄-P loading between control and subsurface-banded litter plots. TP loading in

surface-applied litter plots was significantly higher ($\alpha = 0.05$) than control plots. There was no significant difference ($\alpha = 0.05$) found in the TP loading between control and subsurface-banded litter plots and surface and subsurface-banded litter plots. These results suggest that subsurface application of broiler litter is a better method than surface application to reduce P loss in subsurface flow. $\text{NO}_3\text{-N}$ loading was also reduced by 52% in leachate of subsurface-banded litter plots in comparison with surface-applied litter. Though no reduction was observed in the case of $\text{NH}_4\text{-N}$, since there was no reduction in $\text{NH}_4\text{-N}$ concentration in leachate. Overall, subsurface application of litter proved to be a better method to control nutrient loss in subsurface flow.

Although concentration of $\text{PO}_4\text{-P}$ and TP was less in leachate in comparison with surface runoff in all the plots, the loading of $\text{PO}_4\text{-P}$ and TP was greater in leachate than surface runoff (Fig. 4.13 & 4.14). This is not surprising, since more than 90% of the water infiltrated, this made the product of concentration and volume of water much higher in subsurface flow. $\text{PO}_4\text{-P}$ and TP loading was about 65 and 42%, respectively, more in leachate than surface runoff from surface-applied litter plots. In subsurface-banded litter plots, TP loading was about 82% more in leachate in comparison with surface runoff. Although in subsurface-banded litter plot, $\text{PO}_4\text{-P}$ loading was slightly higher in surface runoff, i.e., about 25% in comparison with leachate, in case of control plots too $\text{PO}_4\text{-P}$ and TP loading was about 16 and 43%, respectively, more in leachate than surface runoff. This shows that subsurface transport of P can transfer significant amount of P than surface runoff in this region. Similar trend in standard deviation was seen in the leachate loading as was seen in the leachate concentration (Fig. 4.11 & 4.12).

4.3.3.3 Percentage of Mehlich-1 Extractable Phosphorus Loss in Surface Runoff and Leachate

The Mehlich-1 extractable P (M1-P) was calculated in total volume of the soil within each plot above lysimeter i.e. (3.05 m by 1.52 m by 0.5 m). The percentage of M1-P loss in runoff and leachate as a percentage of initial soil M1-P level and P added by broiler litter is from each plot is shown in Fig. 4.15. The percentage of M1-P loss was less than 1% in all the plots irrespective of the treatment. This result supports the previous study by Sharpley et al. (1999) that M1-P loss is not of concern of a farmer as it represents small fraction (1 to 2%) of P applied. In surface-applied litter plots M1-P loss was significantly higher ($\alpha = 0.05$) than control and subsurface-banded litter plots. In subsurface-banded litter plots, M1-P loss was very close M1-P loss in control plots. In fact there was no significant difference ($\alpha = 0.05$) found in P loss between control and subsurface-banded litter plots. This result show that in subsurface-banded litter plots most of the M1-P stayed in the trench where broiler litter was applied.

4.4 CONCLUSIONS

Method of litter application plays an important role in P transport in surface and subsurface flow. In surface runoff, concentration and loading of nutrients was significantly reduced when broiler litter was subsurface-banded instead of broadcasting it. In fact, concentration of nutrients in surface runoff of subsurface-banded litter plots didn't differ significantly from that of control plots. Less than 10% of rainfall contributed to surface runoff in all the plots irrespective of the treatment. More than 90% of the water infiltrated into the soil. The concentration of all nutrients in leachate/subsurface flow was less than the corresponding concentration of that nutrient in surface runoff. The trends in loading of nutrients in

leachate/subsurface flow were not similar to concentration in subsurface flow. The loading of all the nutrients was more in subsurface flow in comparison with loading in surface runoff. This was probably because of large volume of water infiltrating down in the soil. These results show that subsurface transport of P is at least as important in this region as the surface transport. Most of the BMPs are designed to reduce P loading in surface runoff rather than subsurface flow. Along with preventing P loss in surface runoff, focus should be made to reduce P loss in subsurface flow too to prevent the water quality of surface waterbodies in this region. New BMPs should be developed which can help in reducing P loss in subsurface flow.

Table 4.1. Selected properties of soil for the 0 to 5 cm depth before the litter application.

Parameter	Value*
pH	5.13 (0.02) [†]
NH ₄ -N (mg/kg)	21.59 (0.67)
NO ₃ -N (mg/kg)	13.22 (0.79)
TN (%)	0.14 (0.19)
M1-P (mg/kg)	37.37 (0.45)
PO ₄ -P (mg/kg)	4.61 (0.67)

* Mean of 27 samples

[†] Coefficient of variation

Table 4.2. Composition of broiler litter applied to fescue pasture.

Parameter	Value
pH	8.69
NH ₄ -N (mg/kg)	1203.15
NO ₃ -N (mg/kg)	110.77
TN (%)	2.94
TP (mg/kg)	19278.36
PO ₄ -P (mg/kg)	3114.43

Table 4.3. Water budget for the experiment showing amount of rainfall applied, runoff generated, volume of leachate, and percentage of rainfall which contributed to surface runoff and leachate

	Litter Treatment		
	Control plots	Surface-applied litter plots	Subsurface-banded litter plots
Rainfall (m ³)	0.56 a	0.51 a	0.58 a
Runoff (m ³)	0.05 a	0.04 a	0.04 a
Leachate (m ³)	0.39 a	0.33 a	0.27 a
Percentage of rainfall contributed to runoff	8.9	7.8	6.8
Percentage of rainfall contributed to leachate	69.64	64.7	46.55

Within each row means followed by the same letter are not significantly different at $\alpha = 0.05$ (LSD).

Table 4.4. Flow weighted concentrations of selected constituents in surface runoff from fescue control, surface-applied, and subsurface-banded litter plots

Runoff constituent	Control plots	Surface- applied litter plots	Surface-applied litter plots
	mgL ⁻¹		
NH ₄ -N	0.43 a (0.09) †	1.67 b (0.58)	0.33 a (0.09)
NO ₃ -N	0.40 a (0.06)	3.25 b (1.41)	0.83 a (0.03)
PO ₄ -P	0.37 a (0.11)	3.43 b (1.43)	0.42 a (0.08)
TP	0.69 a (0.18)	6.01 b (0.58)	1.02 a (0.03)

¥ Within each row means followed by the same letter are not significantly different at $\alpha = 0.05$ (LSD).

† Standard Deviation

Table 4.5. Concentrations of selected constituents in leachate from control, surface-applied, and subsurface-banded litter plots

Leachate Constituents	Control plots	Surface-applied litter plots	Subsurface-banded litter plots
		mgL ⁻¹	
NH ₄ -N	0.35 b (0.31)	1.29 a (0.57)	1.65 a (0.17)
NO ₃ -N	2.56 a (3.19)	3.02 a (1.46)	1.72 a (0.27)
PO ₄ -P	0.07 b (0.07)	1.20 a (0.33)	0.05 b (0.07)
TP	0.17 b (0.14)	1.32 a (0.48)	0.83 a (0.25)

¥ Within each row means followed by the same letter are not significantly different at $\alpha = 0.05$ (LSD).

† Standard Deviation



Fig. 4.1. Rear view of subsurface band applicator used to make trenches for subsurface application of broiler litter.



Fig.4. 2. Zero tension pan lysimeter filled with polypropylene beads



Fig.4. 3. Passive fiberglass wick lysimeter



Fig. 4.4. Wick and pan lysimeters installed 50 cm below soil surface



Fig. 4.5. Runoff sample collection at the downslope end of the plot



Fig.4. 6. Carboy filled with leachate at the end of the rainfall event.

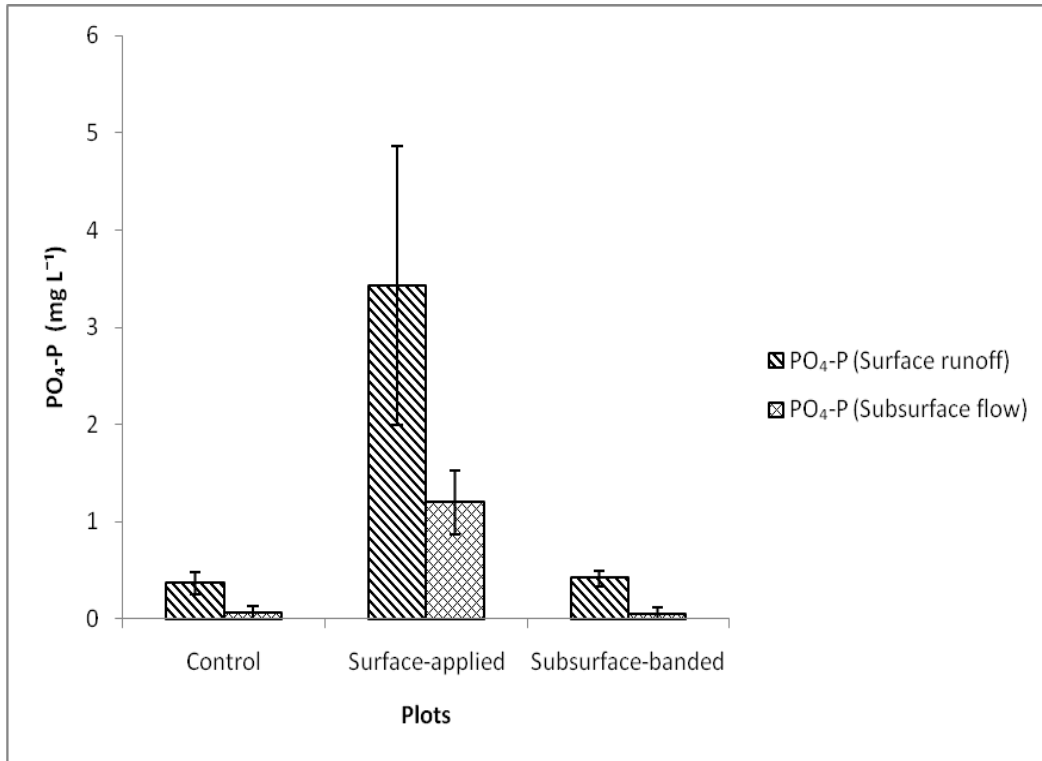


Fig. 4.7. Comparison of PO₄-P concentration in control, surface-applied and subsurface-banded litter plots in surface and subsurface flow. Total bar length is two standard deviations.

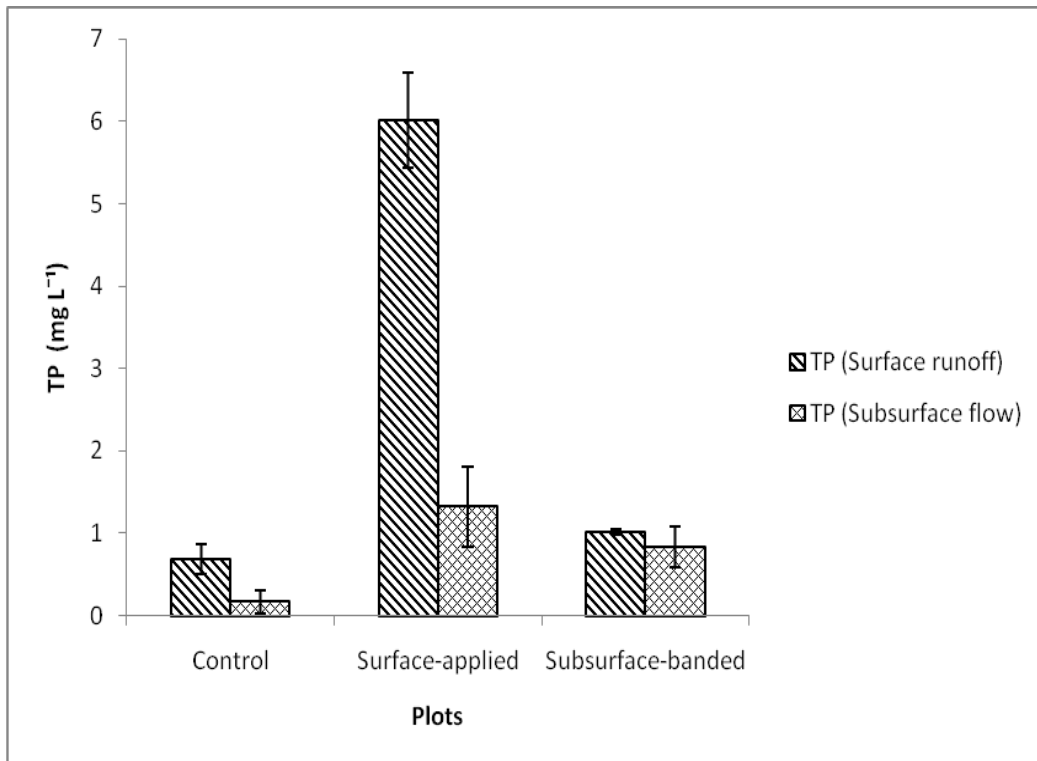


Fig.4. 8. Comparison of TP concentration in control, surface-applied and subsurface-banded litter plots in surface and subsurface flow. Total bar length is two standard deviations.

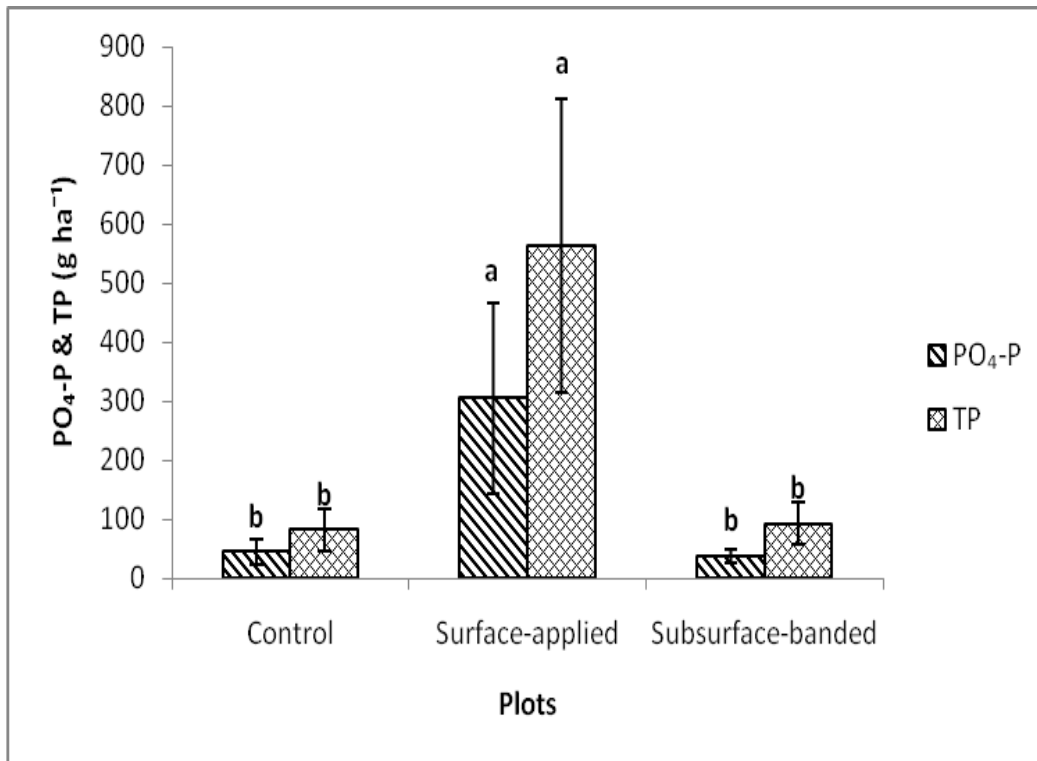


Fig. 4.9. PO₄-P and TP loading from control, surface-applied and subsurface-

banded litter plots in surface runoff. Total bar length is two standard deviations.

Bars with same letter and same nutrient indicates no significant difference between different treatments at LSD 0.05 level

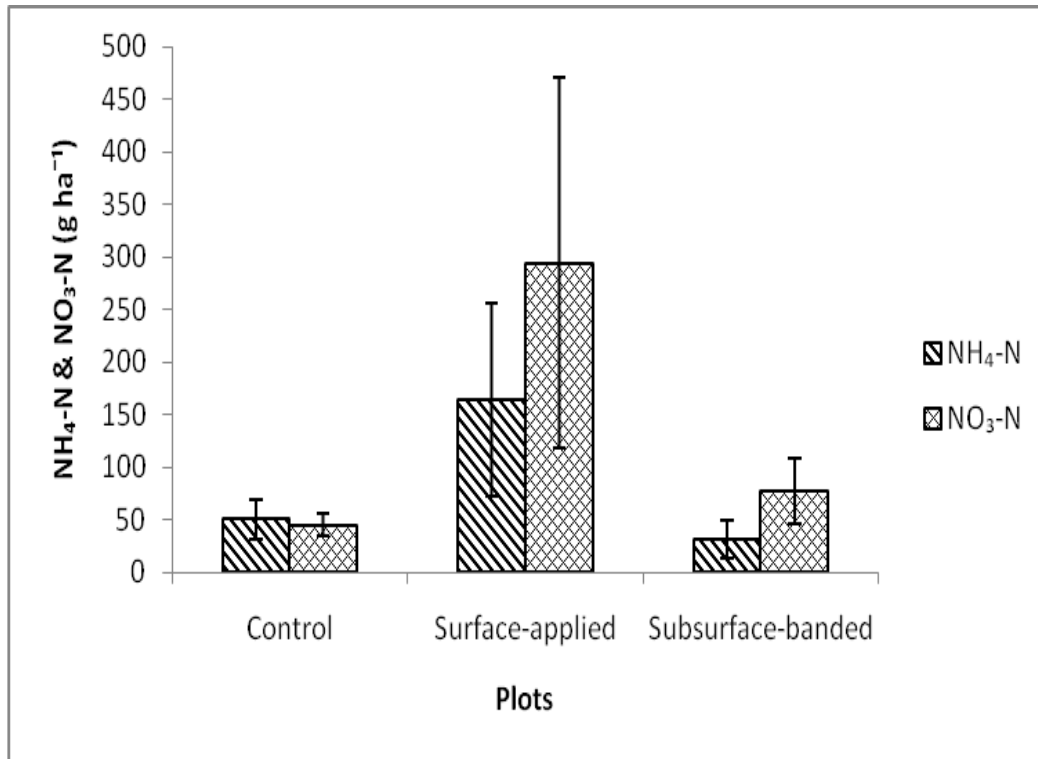


Fig. 4.10. NH₄-N and NO₃-N loading from control, surface-applied, and subsurface-banded litter plots in surface runoff. Total bar length is two standard deviations.

Bars with same letter and same nutrient indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

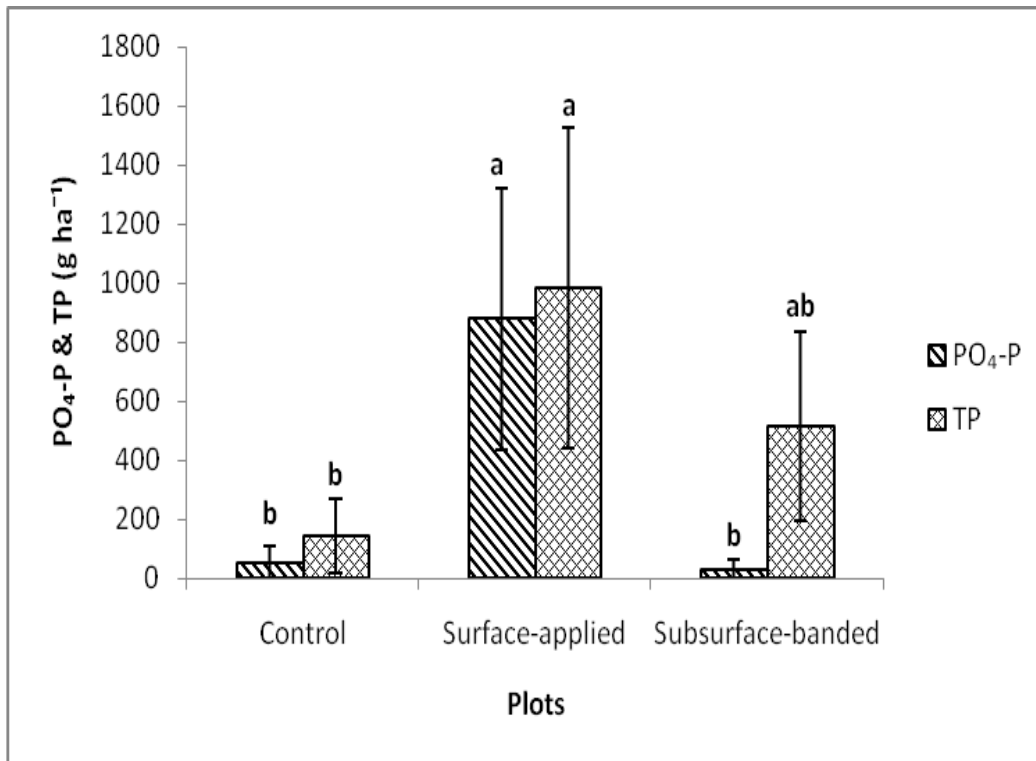


Fig. 4.11. PO₄-P and TP loading from control, surface applied, and subsurface-banded litter plots in subsurface flow. Total bar length is two standard deviations. Bars with same letter and same nutrient indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

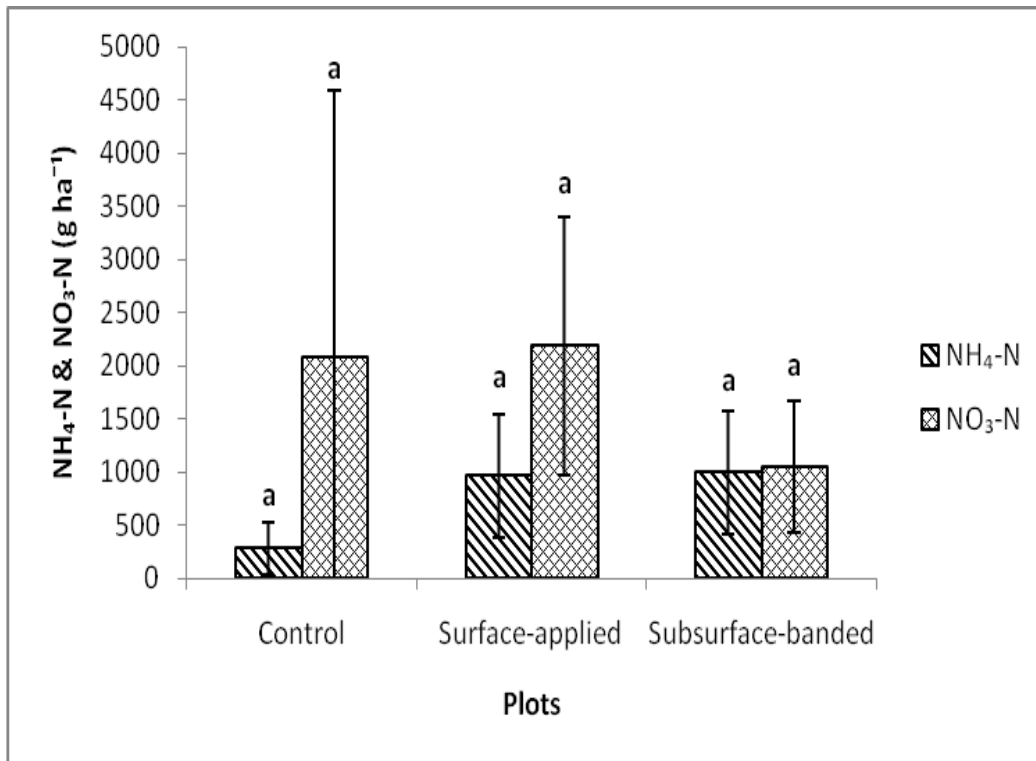


Fig. 4.12. NH₄-N and NO₃-N loading from control, surface-applied, and subsurface-banded litter plots in subsurface flow. Total bar length is two standard deviations. Bars with same letter and same nutrient indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

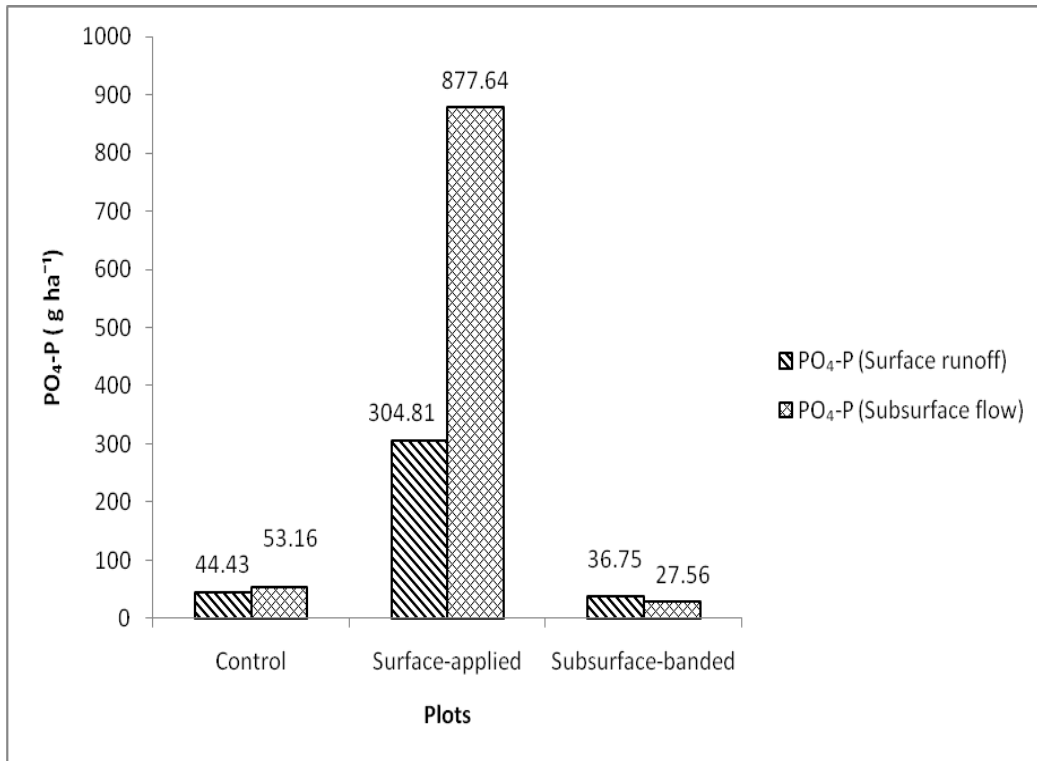


Fig. 4.13. Comparison of PO₄-P loading in surface runoff and subsurface flow from control, surface-applied, and subsurface-banded litter plots.

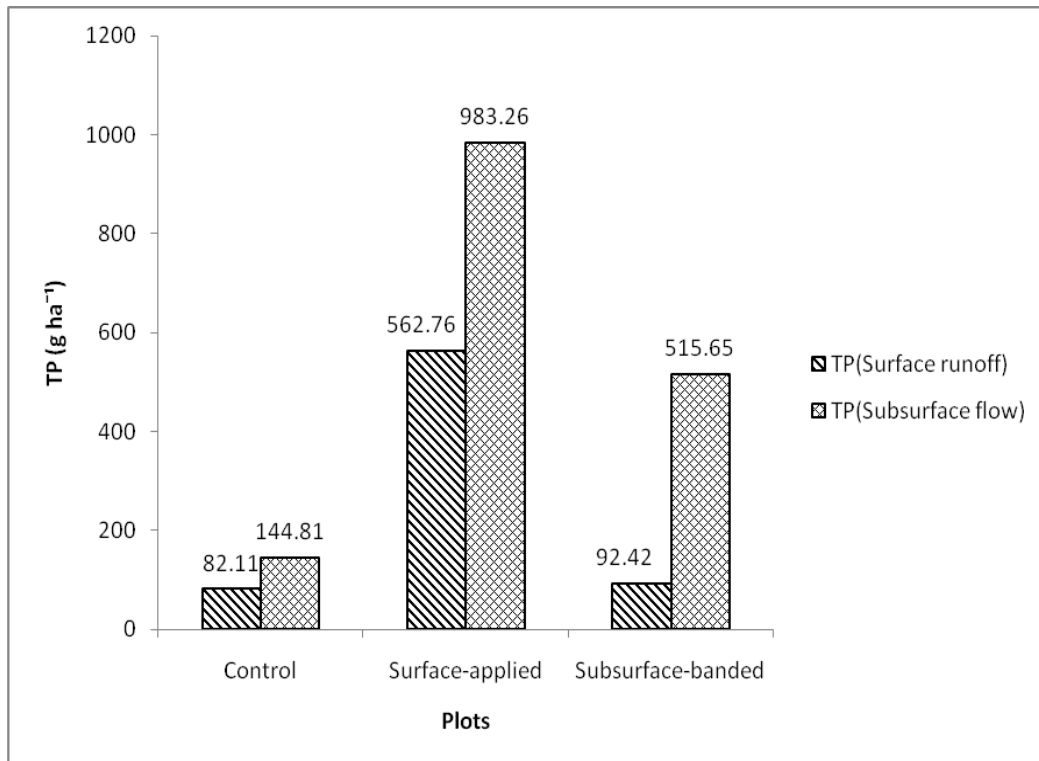


Fig. 4.14. Comparison of TP loading in surface runoff and subsurface flow from control, surface-applied, and subsurface-banded litter plots.

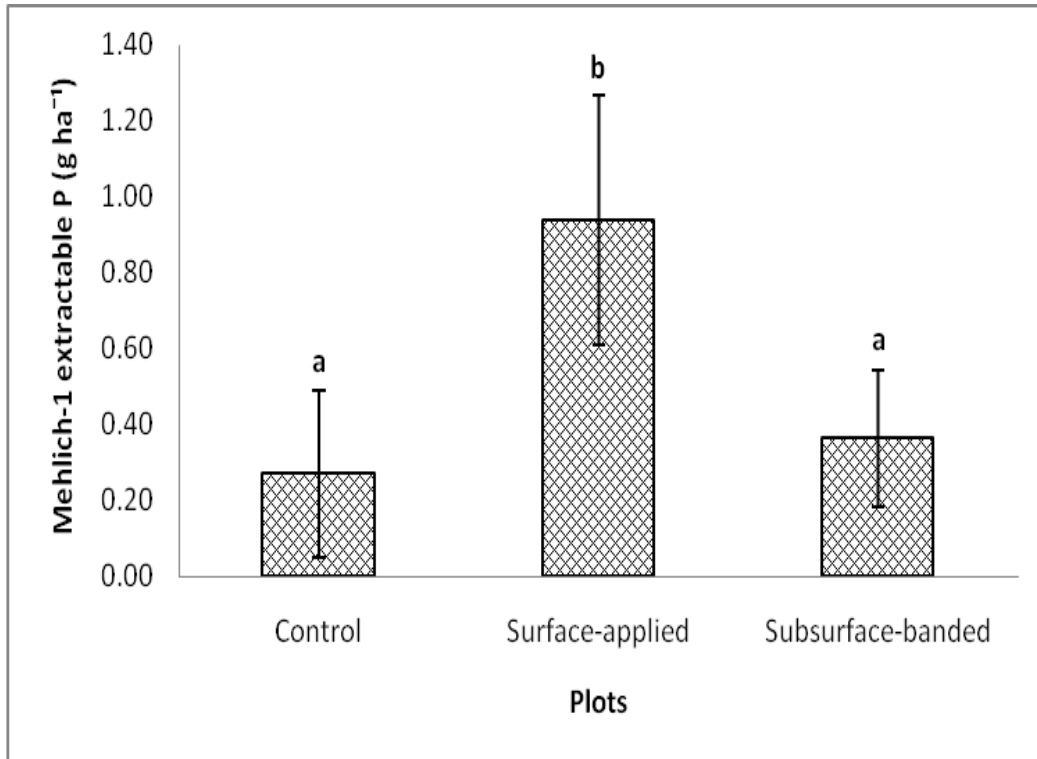


Fig. 4.15. Percentage of Mehlich-1 extractable P loss of the initial TP in plot

and TP added by broiler litter from control, surface-applied, and subsurface-banded litter plots. Total bar length is two standard deviations.

Bars with same letter indicates no significant difference between different treatments at $\alpha = 0.05$ (LSD).

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

The results of this study revealed some new results about the effect of broiler litter application method on fate and transport of P. The results from plot scale rainfall simulation experiment showed that the method of broiler litter application plays an important role in surface and subsurface transport of P. Surface and subsurface water quality improved with subsurface application of broiler litter in comparison with surface application of litter. Loss of all nutrients was reduced significantly when broiler litter was subsurface-banded and was very close to that of control plots.

A plot scale rainfall simulation experiment was conducted at the Sand Mountain Region of north Alabama. Nine plots with sheet metal borders and with gutter at downslope end to collect surface runoff were constructed. There were three replications of each surface, subsurface-banded litter and control (no litter) plots. To know the quality and quantity of water leaching down, pair of pan and wick lysimeter was installed 50 cm below soil surface. These lysimeters drained the water to the carboys through the polypropylene tubing. To install lysimeters beneath soil surface a new method of installation was developed which disturbed the soil to the minimal extent. This method consisted of pair of lysimeters and pushing boxes which were pushed in the soil using tractor hydraulics. This method made the lysimeter installation

process much easier. All the runoff and leachate samples collected were analyzed for different nutrient concentrations. Based on the field experimentation results the following conclusions were made.

OBJECTIVE 1

The first objective was to compare nutrient loss in surface runoff from surface and subsurface-banded broiler litter.

Results showed that the broiler litter application method affects the nutrient loss in surface runoff. The concentration of all the nutrients was significantly reduced in surface runoff of plots with subsurface-banded broiler litter. The mass loss of nutrients also followed the similar trend to concentration of nutrients. This might be because in subsurface application of litter, surface runoff doesn't come in direct contact with broiler litter applied in trenches. The concentration and mass loss in surface runoff of subsurface-banded litter plots was very close to that of control plots. The result of this study also showed that only less than 10% of the rainfall contributes to surface runoff and more than 90% of water is infiltrating down.

Since subsurface application of litter helped in reducing nutrient concentration and loss in surface runoff from plots, therefore we fail to reject the hypothesis

OBJECTIVE 2

This objective was to develop a new method of installation of pan and wick lysimeter in soil.

This method made the lysimeters installation process much easier and provided minimal disturbance to the soil. The boxes used for the installation acted as good support structures to hold the ceiling of the tunnel where lysimeters were installed.

OBJECTIVE 3

The second objective was to compare P loss in surface and subsurface flow from surface and subsurface-banded broiler litter.

Results of this study showed that significant amount of P loss from fields in this region occurs via subsurface flow too along with surface runoff. Subsurface application of litter helped in reducing the concentration and loss of nutrients via subsurface flow. This can be due to the fact that during subsurface application of broiler litter, subsurface applicator might have closed the macropores in the trench which prevented water from going down in soil profile. The concentration of all the nutrients analyzed in subsurface flow reduced in comparison with their corresponding concentration in surface runoff. This was due to the fact that broiler litter had more interaction with surface runoff in comparison with subsurface flow. Since more than 90% of the water was infiltrating down in the soil, loading of all the nutrients was more in subsurface flow in comparison with surface runoff. This suggests that though subsurface application of nutrients helps in reducing the concentration of nutrients in subsurface flow, but not the loading of nutrients via subsurface flow. This suggests that subsurface flows in this region are critical and could transfer significant amount of P from broiler litter fertilized fields to rivers and streams, therefore we fail to reject the hypothesis i.e. subsurface transport of phosphorus is important in the region.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Based on the results of this study, subsurface transport of P to streams and rivers is as important as surface transport of P in this region. Along with preventing the loss of P in surface runoff, reducing the loss of P via subsurface flow should also be considered. New best

management practices (BMPs) should be developed which can prevent the P loss in subsurface flow and reduce the transfer of P to surface body.

REFERENCES

- ACES. 2007. State of Alabama poultry production. Available at <http://www.aces.edu/poultryventilation/documents/NPTCIndustryFactSheet.pdf>. ACES, Alabama A&M and Auburn Universities. (verified 18 November. 2009)
- Aksoy, B., H.T. Cullinan, N.E. Sammons Jr, M.R. Eden. 2008. Identification of optimal poultry litter biorefinery location in Alabama through minimization of feedstock transportation cost. *Environ Progress*. 27:515-523.
- Baker, J.L., K.L. Campbell, H.P. Johnson, and J.J. Hanway. 1975. Nitrate, phosphorus, and sulfate in subsurface drainage water. *J. Environ. Qual.* 4:406–412.
- Barbee, G. C., and K. W. Brown. 1986. Comparison between suction and free-drainage soil solution samplers. *Soil Sci.* 141:149–154.
- Barzegar, A.R., S.J. Herbert, A.M. Hashemi, and C.S. Hu. 2004. Passive pan sampler for vadose zone leachate collection. *Soil Sci. Soc. Am. J.* 68:744–749.
- Boll, J., T.S. Steenhuis, and J.S. Selker. 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. *Soil Sci. Soc. Am. J.* 56:701–707.
- Brandi-Dohrn, F.M., R.P. Dick, M. Hess, and J.S. Selker. 1996. Field evaluation of passive capillary samplers. *Soil Sci. Soc. Am. J.* 60:1705–1713.
- Brinson, S., M.L. Cabrera, and S. Tyson. 1994. Ammonia volatilization from surface-applied, fresh and composted poultry litter. *Plant Soil* 167:213–218.
- Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 1999. An equilibrium tension lysimeter for measuring drainage through soil. *Soil Sci. Soc. Am. J.* 63:536–543.

Burwell, R.E., G.E. Schuman, K.E. Saxton, H.G. Heinemann, and R.G. Spomer. 1977. Nitrogen and phosphorus movement from agricultural watersheds. *J. Soil Water Conserv.* 32:226–230

Bremner, J.M. 1965. Total nitrogen. P. 1149-1178. *In* C.A. Black et al. (ed.) *Methods of soil analysis. Part 2. Agron. Monogr. 9.* ASA, Madison, WI.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Applic.* 8:559–568.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. *J. Environ. Qual.* 29:1582–1586.

Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. *J. Environ. Qual.* 27:251–257.

Edwards, D.R., and T.C. Daniel. 1994. Quality of runoff from fescuegrass plots treated with poultry litter and inorganic fertilizer. *J. Environ. Qual.* 23:579–584.

Farm Show Publishing, Inc. 2009. Prototype applicator buries poultry litter. *Farm Show* 33(2):25. Lakeville, MN: Farm Show Publishing, Inc.

Hansen, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. *J. Soil Water Conserv.* 57:408–417.

Hue, N.V. and C.E. Evans. 1986. *Procedures used for Soil and Plant Analysis by the Auburn University Soil testing Laboratory, Alabama Agric. Exp. Stn., Auburn University.*

Goyne, K.W., R.L. Day, and J. Chorover. 2000. Artifacts caused by collection of soil solution with passive capillary samplers. *Soil Sci. Soc. Am. J.* 64:1330–1336.

Holder, M., K.W. Brown, J.C. Thomas, D. Zabcik, and H.E. Murray. 1991. Capillary-wick unsaturated zone soil pore water sampler. *Soil Sci. Soc. Am. J.* 55:1195–1202.

Jemison, J. M., Jr. and R. H. Fox. 1992. Estimation of zero-tension pan lysimeter collection efficiency. *Soil Sci.* 154:85-94.

John , M.K. 1972. Automated Digestion System for Safe Use of Perchloric Acid. *Analytical Chemistry* 44 (2): 429-430.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen: Inorganic forms. p. 643–698. In A.L. Page et al. (ed.) *Methods of soil analysis. Part 2. Chemical and microbiological properties.* 2nd ed. SSSA Book Ser. 5. SSSA, Madison, WI.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Environ. Qual.* 23: 139–147.

Knutson, J.H., S.B. Lee, W.Q. Zhang and J.S. Selker. 1993. Fiberglass wick preparation for use in passive capillary wick soil pore-water samplers. *Soil Sci. Soc. Am. J.* 57:1474–1476.

Lamba, J. S. 2009. Surface and subsurface transport of phosphorus from surface and subsurface applied poultry litter. MS thesis. Auburn, Ala.: Auburn University, Department of Civil Engineering.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends in a Typic Umprabuult. *Agron. J.* 83:77–85.

Mitchell, C.C., and J.O. Donald. 1995. The value and use of poultry manures as fertilizer. *An. Cir. (Rosario):ANR-244 Ala. Coop. Ext. Serv., Auburn University, AL.*

Moore, P.A., Jr., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management: Environmentally sound options. *J. Soil Water Conserv.* 50:321–327.

Murphy, J., and J.R. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.* 27:31–36.

National Phosphorus Research Project. 2005. National research project for simulated rainfall: Surface runoff studies. Southern Ext. Res. Activity Inf. Ex. Group 17. Available at <http://www.ars.usda.gov/main/docs.htm?docid=2300> (verified 18 November, 2009)

Nichols, D.J., T.C. Daniel, and D.R. Edwards. 1994. Nutrient runoff from pasture after incorporation of poultry litter or inorganic fertilizer. *Soil Sci. Soc. Am. J.* 58:1224–1228.

Pote, D.H., W.L. Kingery, G.E. Aiken, F.X. Han, P.A. Moore, Jr., and K. Buddington. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. *J. Environ. Qual.* 32:2392–2398.

Ross, I.J., S. Sizemore, J.P. Bowden, and C.T. Haan. 1979. Quality of runoff from land receiving surface application and injection of liquid dairy manure. *Trans. ASAE* 22:1058–1062.

SAS Institute. 1999. SAS/STAT user's guide. Version 8. SAS Inst., Cary, NC.

Schroeder, P.D., D.E. Radcliffe, and M.L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. *J. Environ. Qual.* 33:2201–2209.

Self-Davis, M.L., P.A. Moore, Jr., and B.C. Joern. 2000. Determination of water- and/or dilute salt-extractable phosphorus. p. 22–24. In G.M. Pierzynski (ed.) *Southern Coop. Ser. Bull.* 396 [Online]. Available at www.soil.ncsu.edu/sera17/publications/sera17-2/pm_cover.htm (verified 25 August 2009). North Carolina State Univ., Raleigh.

Sen S, P. Srivastava, K.H. Yoo, J.H. Dane, J.N. Shaw, M.S. Kang. 2008. Runoff generation mechanisms in pastures of the Sand Mountain region of Alabama – a field investigation. *Hydrological Processes.* 22: 4222-4232.

Sen S, P. Srivastava, J.H. Dane, K.H. Yoo, J.N. Shaw. 2009. Spatial-temporal Variability and hydrologic connectivity of runoff generation areas in a north Alabama pasture-implication for phosphorus transport. *Hydrological Processes*. DOI: 10.1002/hyp.7502.

Shaffer, K. A., D. D. Fritton, and D. E. Baker. 1979. Drainage water sampling in a wet, dual-pore system. *J. Environ. Qual.* 8:241-246.

Sharpley, A.N., and J.K. Syers. 1979. Loss of nitrogen and phosphorus in tile drainage as influenced by urea application and grazing animals. *N. Z. J. Agric. Res.* 22:127–131.

Sharpley, A.N. 1985. Depth of surface soil–runoff interaction as affected by rainfall, soil slope and management. *Soil Sci. Soc. Am. J.* 49:1010–1015.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992. The transport of bioavailable phosphorus in agricultural runoff. *J. Environ. Qual.* 21:30–35.

Sharpley, A.N. 1993. Assessing phosphorus bioavailability in agricultural soils and runoff. *Fert. Res.* 36:259–272.

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. *J. of Environ Qual.* 23:437–451.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. *J. Soil Water Conserv.* 51:160–166.

Sharpley A.N., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. 1998. Impacts of animal manure management on ground and surface water quality. p. 173–242. In J. Hatfield (ed.) *Effective management of animal waste as a soil resource*. Ann Arbor Press, Chelsea, MI.

Sharpley, A.N., T.C. Daniel, J.T. Sims, J. Lemunyon, R.A. Stevens, and R. Parry. 1999. Agricultural phosphorus and eutrophication. USDA-ARS Rep. 149. U.S. Gov. Print. Office, Washington, DC.

Sharpley, A. 1999. Agricultural phosphorus, water quality, and poultry production: Are they compatible? *Poultry. Sci.* 78:660–673.

Sims, G.K., T.R. Ellsworth, and R.L. Mulvaney. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. *Commun. Soil Sci. Plant Anal.* 26:303–316.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. P losses in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* 27:277–293.

Tewelde, H., S. Armstrong, T. R. Way, D. E. Rowe, and K. R. Sistani. 2009. Cotton response to poultry litter applied by subsurface banding relative to surface broadcasting. *Soil Sci. Soc. Am. J.* 73:384-389.

Timmons, D.R., R.E. Burwell, and R.F. Holt. 1973. Nitrogen and phosphorus losses in surface runoff from agricultural land as influenced by placement of broadcast fertilizer. *Water Resour. Res.* 6:658–667.

Torbert, H.A., R.D. Harmel, K.N. Potter, and M. Dozier. 2005. Evaluation of some P index criteria in cultivated agriculture in clay soils. *J. Soil Water Conserv.* 60:21–29.

Wood, B.H., C.W. Wood, K.H. Yoo, K.S. Yoon, and D.P. Delaney. 1999. Seasonal surface runoff losses of nutrients and metals from soils fertilized with broiler litter and commercial fertilizer. *J. Environ. Qual.* 28:1210–1218.

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

APPENDICES

Appendix A

Strengthening Bar on Lysimeter Boxes

Fig. 3.5 and similar figures that show the lysimeter boxes depict our original design of those boxes. After a trial use of that design, we found that improved structural integrity of the upper trailing end of the lysimeter boxes would be desirable. So, the actual lysimeter boxes used in the project had an additional steel bar that is not shown in Fig. 3.5 and similar figures. The bar was 3 mm thick, was 50 mm in the direction parallel to the sliding direction, and was about 50 mm longer than W_{Lid} . The bar rested on the upper surface of the lid, and the trailing edge of the bar was flush with the trailing edge of the lid. Each end of the bar was welded to the upper surface of the lysimeter box, on either side of the lid, and the bar served to strengthen the trailing end of the box and to better prevent the lid from rising up above its intended position.

During preliminary testing of the steel boxes, we found that the bottoms of the steel boxes needed to be a solid piece of steel that extended the full length and width of the box. We tried using two 3 mm x 50 mm pieces of steel as the bottom of the box, one bar at the leading end and one at the trailing end of the box, with each extending the full width of the box. We found, however, that the strength of this two-bar bottom was insufficient and as the box penetrated a soil wall, the leading bar yielded and caused the sides of the box to yield inwardly. The two tabs at the trailing edge of the lid of each lysimeter box are pivoting tabs, so they can be positioned as shown in Fig A1 to avoid having them interfere with the pushing frame when the pushing frame pushes the lysimeter box.

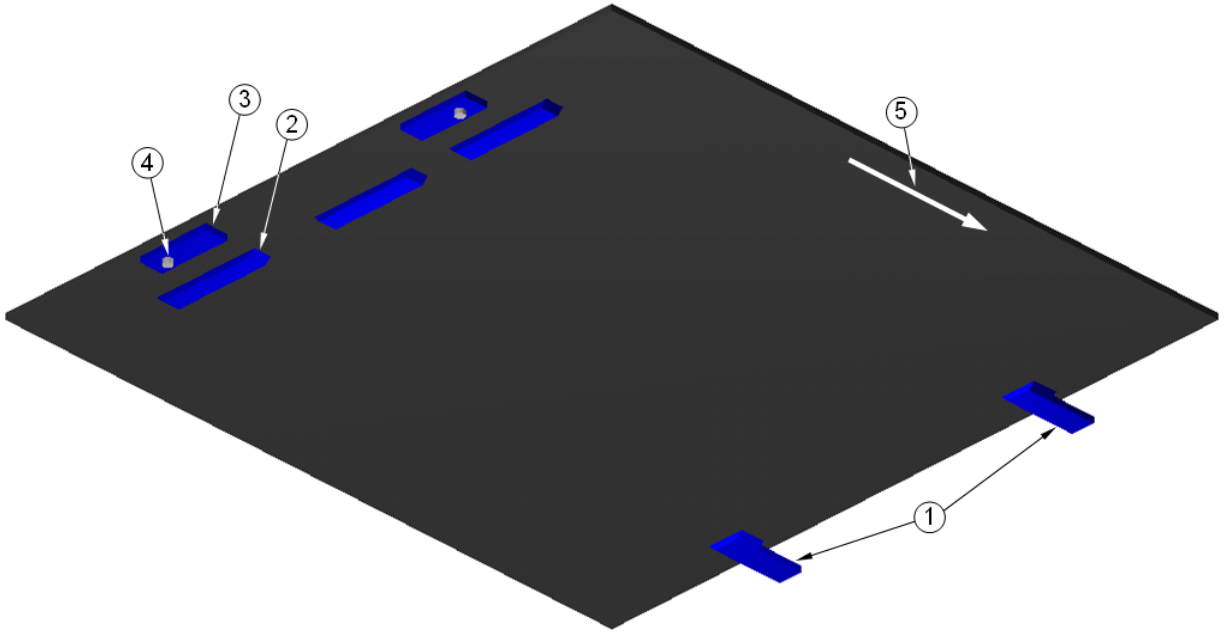


Fig. A1. Lid of lysimeter box, viewed from its lower side: (1) fixed tabs, (2) steel band welded to lid, to guard against soil pivoting a pivoting tab as box slides into soil, (3) pivoting tab, (4) pop rivet for pivoting tab, (5) sliding direction.

The tabs of the lysimeter box, that support the lid, are shown in figures A2 and A3. Rotation of three rotating tabs to allow the trailing end of the lid to be lowered, is shown in figure A4 and removal of the lid of the lysimeter box is shown in figure A5.

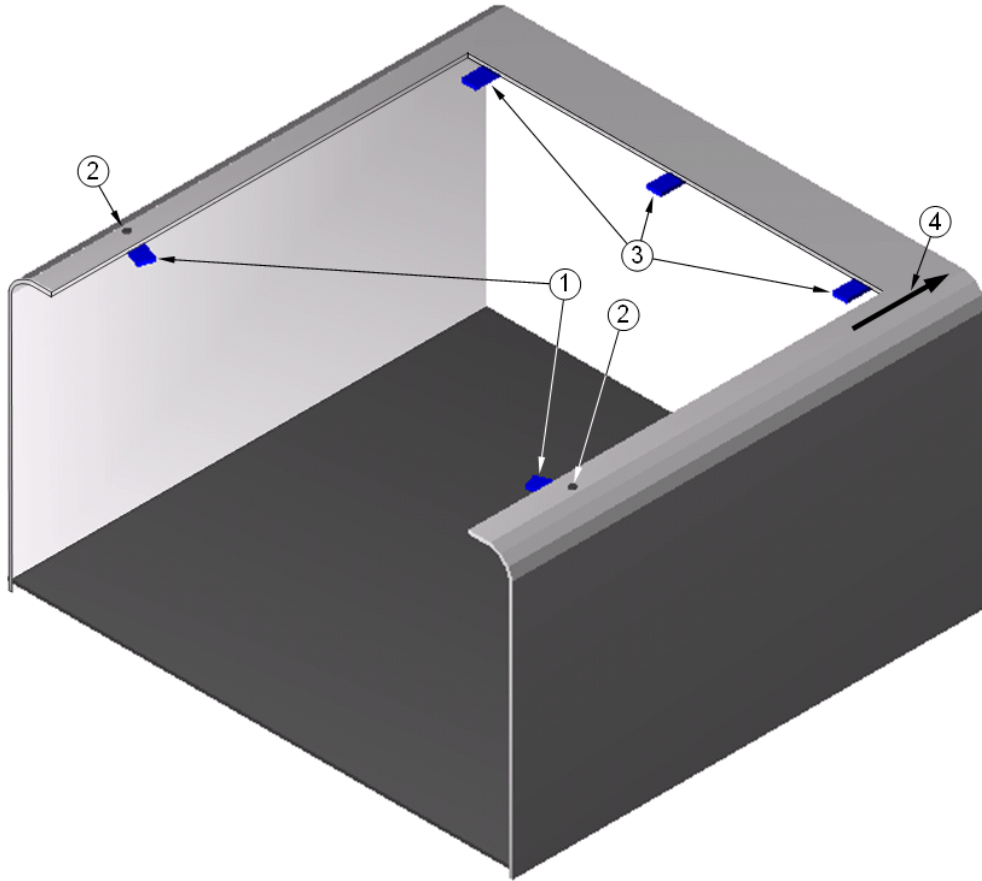


Fig. A2. Lysimeter box, shown with lid removed: (1) pivoting tabs, (2) pop rivets for pivoting tabs, (3) fixed tabs, (4) sliding direction.

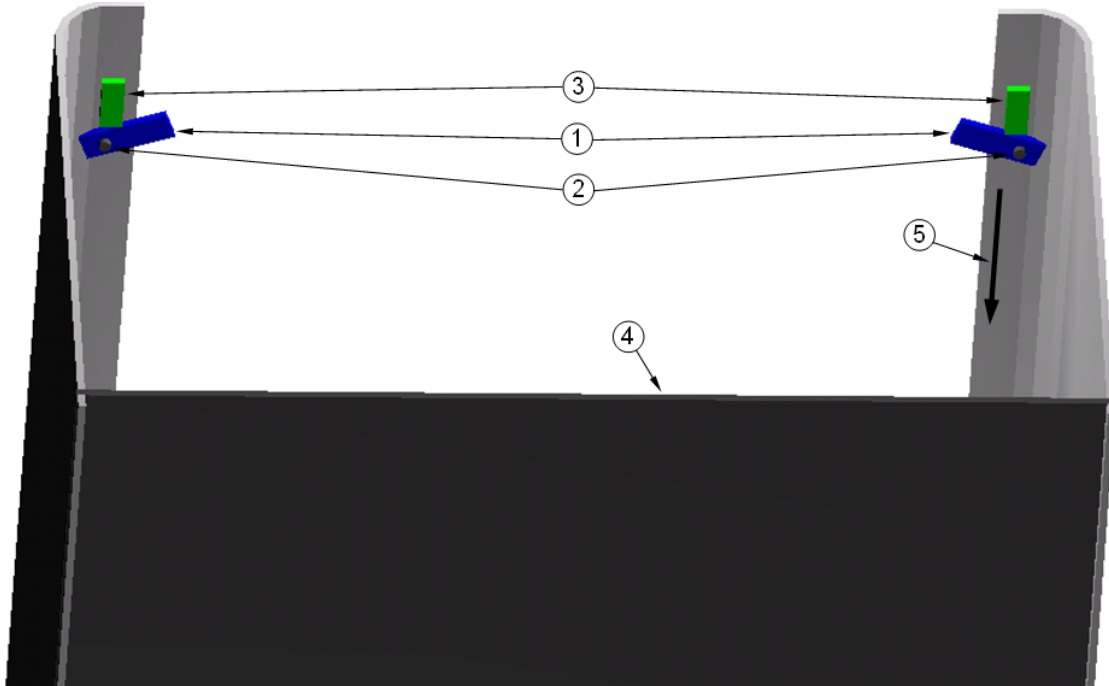


Fig. A3. Trailing end of lysimeter box, shown with lid removed: (1) pivoting tabs, (2) pop rivets for pivoting tabs, (3) steel stops to limit rotation of pivoting tabs while box slides into soil, (4) lower plate of lysimeter box, (5) sliding direction.

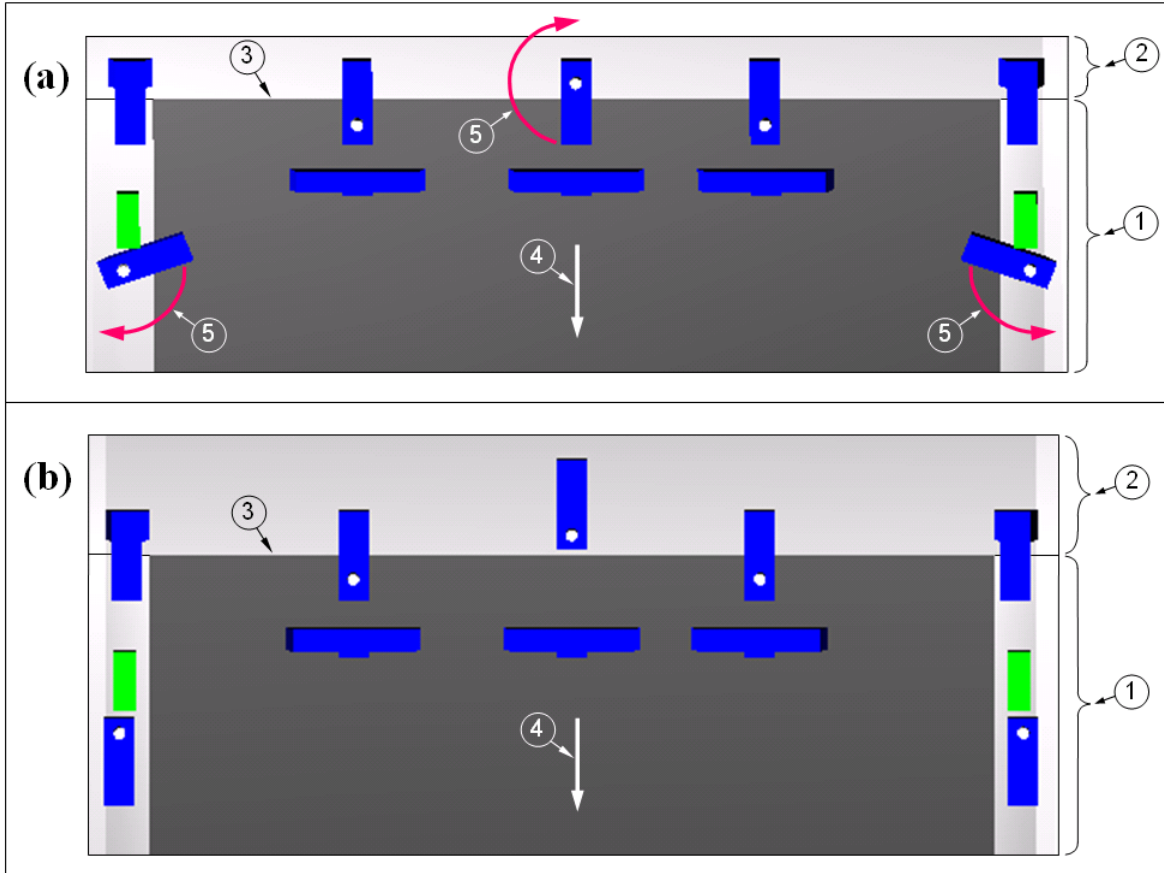


Fig. A4. Views from within lysimeter box and pushing box after soil has been removed from within the boxes. Views looking upward at lower side of the lid: (a) Before the three pivoting tabs that support the trailing end of the lid have been rotated. Arrows show how the tabs are rotated to allow that end of the lid to be lowered. (b) After the three tabs have been rotated. (1) lysimeter box, (2) pushing box, (3) trailing edge of lid, (4) direction in which boxes were pushed into soil, (5) arrows showing rotation of the three rotating tabs.

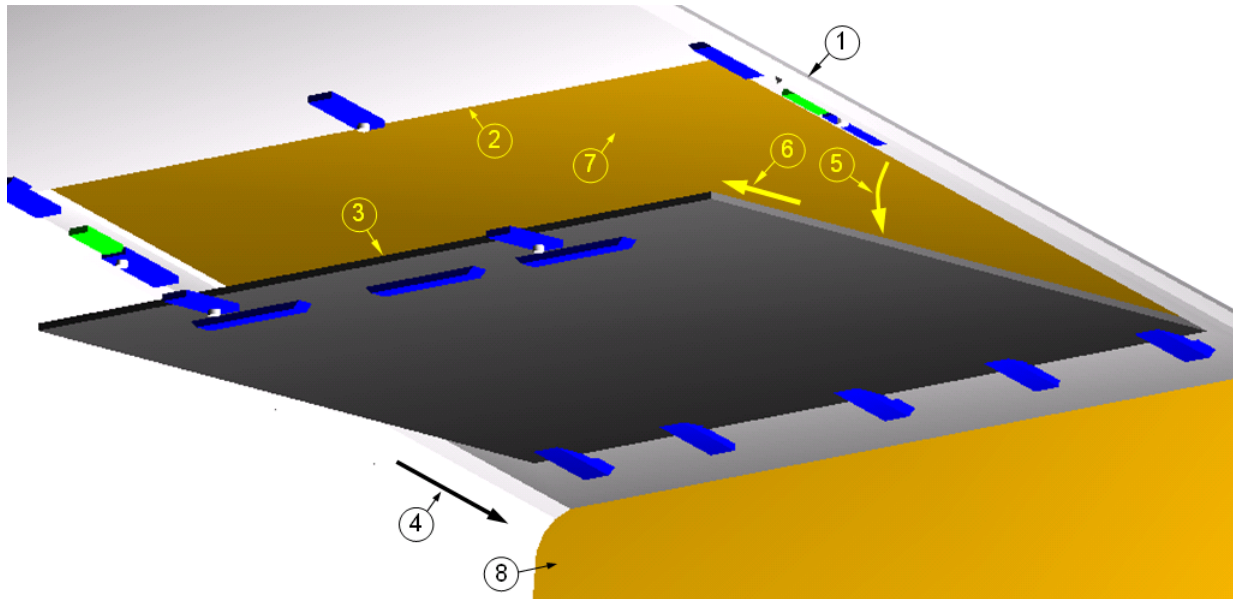


Fig. A5. View showing lower side of lid, to show removal of lid from lysimeter box. For clarity, the vertical wall of the lysimeter box beneath arrow 1 is not shown: (1) lysimeter box, (2) pushing box, (3) lid, (4) direction in which boxes were pushed into soil, (5) rotation of the lid to lower its trailing end, (6) direction in which lid is slid to remove lid from lysimeter box, (7) soil at upper surface of tunnel, (8) vertical wall of soil at end of tunnel.

Before using the 102 mm bore x 203 mm stroke hydraulic cylinder, we used the 51 mm bore x 152 mm stroke hydraulic cylinder and the hand-operated hydraulic pump that were part of the Omega Body Repair Kit. The force needed for pushing a lysimeter box into the soil, however, was sufficiently great that the rod seal, which is the seal around the cylinder rod, failed and began leaking hydraulic oil. We then began using the 102 mm bore x 203 mm stroke hydraulic cylinder powered by a tractor hydraulic system, and this performed much better than the smaller cylinder with its hand-operated pump.