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Preferential Flow and Phosphorus Translocation In Benchmark Soils of West Virginia

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ABSTRACT

Preferential Flow and Phosphorus Translocation in Benchmark Soils of West Virginia

Michael B. Harman

Preferential flow is a mechanistic description of water movement in a soil profile where much of the soil matrix is bypassed during periods of rapid infiltration. The occurrence of preferential flow could lead to the movement of phosphorus (P) down through the soil profile. The objectives of this research were (i) to verify the presence of preferential flow in benchmark West Virginia soil series and (ii) measure soil test phosphorus (STP) levels within the preferential flow pathways and the surrounding soil matrix to determine the effects of preferential flow on phosphorus distribution within the soil profile. A non-reactive dye (Brilliant Blue FD&C) was applied in a ponding application to identify the preferential flow pathways in selected benchmark soil series in pasture management schemes with long-term historical applications of animal waste. The dye applications were excavated and digital images of the preferential flow pathways were taken. Soil samples from the stained (preferential flow paths) and unstained (surrounding soil matrix) portions of the soil profile were collected within each pedogenic horizon and analyzed for STP. All selected series, exhibited preferential flow. STP levels were statistically higher ($p=<0.05$) in the stained soil matrix.

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CHAPTER 1: PHOSPHORUS, AGRICULTURE, & PREFERENTIAL FLOW

Introduction

Amendments to soils, such as nutrients or pesticides, often find a way into waterways. Understanding the source, application method, application rate, and timing of amendments can help identify locations with potential problems. Good management decisions are based on an understanding of how nutrients such as phosphorus (P) move in soil and water. Some methods of potential translocation, such as preferential flow have been overlooked. Recognizing and researching the potential for P loss via preferential flow is needed to protect the environment, and to protect the future of agricultural production in some regions.

Literature Review

Agriculture, Nutrients, and the Environment

The accumulation of nutrients in some agricultural soils is an emerging problem for production agriculture (Pautler and Sims, 2000). Traditionally, concerns about surface water contamination from excess or leached nutrients have focused on nitrogen (N) (Zaimes and Schultz, 2002). N can be difficult to manage due to its mobile nature in the environment. Compared to N, P is much less mobile. By focusing on N losses, P losses were, at times, overlooked. As soil P levels rise, there is growing concern over the soils long-term ability to sorb it and its potential for transport to surface and / or ground water (Maguire and Sims, 2002).

In nearly half of the surveyed waterways in the U.S., N and P enrichment have been cited as damaging to aquatic life via eutrophication, algal blooms, fish kills, and other impairments (Kotak et al., 1994; USEPA, 2007). Elevated nutrients levels in surface waters can lead to conditions which cause negative impacts on recreation, industry, and aquatic life (Gachter et al., 1998). In most fresh water systems, P is the nutrient that is limiting growth (Newton et al., 1999; Conley, 2000). Sufficient levels of P are needed by plants because P is a fundamental component of cell membranes, ATP, and nucleic acids (Newton et al., 1999). However, very small quantities of dissolved P can lead to eutrophication and other related problems (USDA, 1997; Gachter et al., 1998; McGechan, 2002).

Phosphorus Cycling

When considering P sources and the P interactions with the soil, it is simpler to consider P in two fractions, the organic and mineral fractions, and in two states of mobility relative to its availability, labile and non-labile (Syers, 1974; Tate and Newman, 1982; Bowman, 1989). Organic P is P that is an integral component of a larger carbon-containing molecule, such as ATP. Inorganic P is the orthophosphate ion as a component of a primary or secondary mineral such as apatite or bound to a soil mineral surface (Zaimes and Schultz, 2002). Labile P is easily exchanged between the soil solids and soil solution. The dissociation or dissolution of non-labile P takes much longer, perhaps thousands of years or longer (Zaimes and Schultz, 2002).

P ions in soil solution come from several sources. The primary source of mineral P in natural soils is the weathering of primary apatite (Smeck, 1985). Typically, 30 to 75 percent of the soil P is in the organic fraction and it is primarily made up of various biological residues, excreta, and detritus (USDA, 1997; Zaimes and Schultz, 2002). Following an initial rise in soil solution P after new inputs, soluble P concentrations decrease rapidly, and than decrease slowly for several years as P is adsorbed (Barrow and Shaw, 1975a, b).

Several alternative fates await P ions. Some labile P will be converted to secondary P minerals, and some of the secondary P minerals will become encapsulated by Fe and Al oxides (Fig. 1.1). These occluded P minerals effectively become P sinks, ending any cyclical exchange or use (Smeck, 1985). Another common fate of P is incorporation in stable organic pools. In the soil, humus serves as a large reservoir of organic P, which annually releases a portion of that P (USDA, 1997). Soil microbes continually break down the humus and as they die, P ions are transferred to the soil matrix (USDA, 1997).

Soil properties can influence P sorption. Properties that change the type and number of exchange sites, and the chemical reactivity or affinity of the soil for P can increase or decrease the soils ability to sorb P thus influencing its availability for plants and its risk to the environment. Soil types that have a lower pH, higher clay contents, or contain more reactive iron and aluminum oxides tend to have the highest P sorption capacities (Abrams and Jarrell, 1995). Soils that exhibit lower dispersivity and higher adsorption tend to transport less P to surface waters (Zaimes and Schultz, 2002). P is most mobile between pH 5.5 and 7.0

because at low pH, Fe and Al react with P and at high pH, Ca and Mg react with P to limit mobility (Gilmour, 2003).

As P moves in the environment, it is desirable for it to remain sorbed in the soil away from the aquatic environment and available for plants. However P moves, and how it moves is influenced by the various factors and processes outlined above. P could move as a component of an organic molecule or sorbed on a surface (particulate P), as an inorganic compound or in solution. One possible source of P movement often not considered is the movement in soil water.

Soil Water Movement

For nearly 100 years, the scientific community has known that water flow in soils can be uniform or non-uniform (Hendrickx and Flury, 2001). In soil water movement, there are two major mechanistic models -matrix flow and preferential flow- and they have very different impacts on water flow and chemical leaching potential (Hendrickx and Flury, 2001). Matrix or piston flow is a stable sharp wetting front (Fig. 1.2) parallel to the soil surface as water moves downward through the soil profile (Djodjic, 2001). An irregular wetting front or unstable flow, can lead to more rapid movement of water in some areas or preferential flow (Bundt et al., 2001).

Preferential Flow

Preferential flow can occur in homogeneous or heterogeneous soils of sandy, loamy, and clayey textures (Wang et al., 1998). Antecedent soil moisture levels affect the macropore component of preferential flow. Shipitalo and

Edwards (1996) found dryer soils to have higher rates of macropore flow. Bouma et al. (1981) found wetter surface conditions and higher rainfall intensities favor macropore flow. At low intensity lateral infiltration in the macropore walls occurred unless the surface was already saturated and precipitation exceeded infiltration (Bouma et al. 1981). Research has documented preferential flow in saturated (Wilson et al., 1997) and unsaturated conditions (Hammermeister et al., 1982; Jardine et al., 1989; Wilson et al., 1997). Research has noted preferential flow at different depths and textural layers in the soil profile (Heppell et al., 2000a, b). Steenhuis and Parlange (1991) found macropore flow in some instances to be of a greater significance in water movement through the soil profile than matrix flow. Heppell et al. (2002) concluded that macropore flow begins when rainfall intensity exceeds infiltration capacity, or when the soil matrix becomes saturated at a given depth.

In agricultural soils, preferential flow can be quite common (Petersen et al., 1997). Much research has documented this phenomenon in fine textured soils with well-developed structure (Bouma et al., 1977; Flury et al., 1994; Mohanty et al., 1998; Stamm et al., 1998). More structured soils are better suited for water movement, due in part to increased macroporosity (Petersen et al., 1997). The importance of preferential flow tends to increase as the soil pore size increases, particularly in clay soils (Kissel et al., 1973). Preferential flow paths can be the product of interaggregate pores, earthworm burrows, gopher holes, cracks, decayed root channels, and other types of macroporous structures (Nielsen et al., 1986). These interconnected macroporous pathways can contribute to soil water and nutrient loss and an uneven distribution of soil water and nutrients within the soil matrix (Booltink and Bouma, 1991).

Phosphorus, the Environment, and Preferential Flow

It is difficult to determine the threshold at which P concentrations affect eutrophication, and it is possible that this threshold is quite low (Ferguson et al., 1996; Zaimes and Schultz, 2002). In 1976, the U.S. EPA set the level of P associated with accelerated aquatic degradation from eutrophication at 0.05 mg/L for dissolved P and 0.1 mg/L for total P (USDA, 1997). In most freshwater ecosystems, algae and aquatic plants acquire their nutrients from sediments, surface water, and groundwater inputs (Newton et al., 1999). In the environment, particulate P can be sorbed on or in a compound with calcium, iron, or aluminum. Under conditions such as low dissolved oxygen, some of the iron P compounds can become bio-available (Newton et al., 1999). Under conditions such as low pH, the P in some of the calcium compounds can become bio-available (Newton et al., 1999). Atmospheric deposition of P can contribute to eutrophication as well (USDA, 1997). Even several years after deposition, P associated with sediments can sustain aquatic plant and algal growth (Jacoby et al., 1982; USDA, 1997). This long-term release further complicates efforts to identify impacts of current inputs into freshwater ecosystems.

Research has shown that preferential flow can increase the speed of through profile movement of free moving compounds such as chloride, bromide, and nitrate (Quisenberry and Phillips, 1976; Bouma, 1980; Quisenberry et al., 1994). Research has also shown that preferential flow can increase the speed of through profile movement of compounds that do not move freely in soils and sorb to the soil matrix, such as P (Cox et al., 2000). Brye et al. (2002) found elevated nutrient levels in leachate collected with soil tension lysimeters in a restored tall grass prairie and under corn production, and suggested that a significant portion of the nutrients measured in the samples were moving within preferential flow paths. Bundt et al. (2000) studied spatial distribution of sorbing radionuclides (cesium^{137}, lead ^{210}, americium ^{241}, plutonium $^{238, 239, 240}$) in relation to preferential flow pathways in a forest soil based on identified pathways from dye applications, and found a significant influence of preferential flow on the distribution of the radionuclide. Shipitalo and Gibbs (2000) applied dye tracers to biopores and verified flow into tile drains in 14 minutes when soil series permeability ratings suggested it should have taken at least 12 hours. These findings suggest that preferential flow may move both sorbing and non-sorbing compounds though soil profiles and perhaps into ground or surface waters.

Grant et al. (1996) found P losses from subsurface drainage in two forms, dissolved P and particulate P. Particulate P losses can come from movement of P-laden compounds and P adsorbed to mineral and organic materials moving in the soil water (Grant et al., 1996). Hodgkinson et al. (2002) documented particulate P loss from the subsurface drainage from a field with a clayey texture, and noted the highest levels occurred after the first storm event following manure applications, indicating transmission of surface applied manure via macropore flow. Oygarden et al. (1997) also examined subsurface drainage in clay soils. They identified macropores in soil cores with computed tomography and measured the sediment in tile drains. This data showed higher sediment levels in the drainage when the soil surface was plowed indicating that soil materials were moving through the subsoil, most likely within the macropores. The research of Campbell et al. (1995) involved modeling the surface/subsurface partitioning of P contribution in streams based on water quality, groundwater quality and overland flow data. They concluded that in some pastures subsurface flow may be the primary flow path by which P is transferred from the farm to the environment and it is unlikely that traditional measures to control it will yield significant reductions in soil P losses. These studies tend to buttress the concept of particulate and dissolved compounds moving through a soil profile via macropore flow and/or preferential flow.

Food Animal Agriculture Production

Elevated levels of P in the soil have been attributed to applications of animal manures as a fertilizer to satisfy N requirements. Historically, animal manures have been over-applied on some farms near confined animal feeding operations. Grant, Hardy, and Pendleton Counties of West Virginia account for 15% of West Virginia’s cattle sales (Fig. 1.3) or approximately 35,439 head, and 85% of West Virginia’s broilers and other meat-type chicken sales (Fig. 1.4) or approximately 77,419,965 chickens (NASS, 2002). When combined, regionally high densities of food animal agriculture and N based manure applications in excess of crop removal capabilities can lead to elevated P saturation and an increased risk of water quality impairment (Beck et al., 2004).

The manures associated with concentrated animal production in Grant, Hardy, and Pendleton Counties are used in many ways. Of primary interest is its use as fertilizer for row crops and pastures. Row crop production has the capacity to remove a portion of the soil P via harvest. Pastures more closely resemble a closed system, such that the only P export is the P in animal tissues or forages removed from the farm. Only 26% of the total farm acres in Grant, Hardy, and Pendleton Counties are cropland (NASS, 2002). If all agricultural land uses receive similar applications of manure, P retention in grass pastures and hayfields may be environmentally important.

In 1994, a voluntary survey of poultry producers in Grant, Hampshire, Hardy, Mineral, and Pendleton Counties yielded much needed data about the production and use of poultry manure. Of the nearly 200 surveyed producers, 53% responded in whole or part to the questions (Basden et al., 1994). This study determined 57% of the farms generated greater than 200 tons of poultry manure per year (Basden et al., 1994). Almost 63% of the farms were less than 250 acres in size and about 84% identified their farms as mainly grassland farms (Basden et al., 1994). Almost 60 percent of these poultry farms contained no acreages of cropland and the responding farmers estimated they applied over 70% of the manure to grasslands as fertilizer (Basden et al., 1994). This survey data is consistent with P accumulation in grassland soils of eastern West Virginia as seen in West Virginia University (WVU) Soil Testing Laboratory results.

Soil Test Phosphorus levels in West Virginia

West Virginia University (WVU) Soil Testing Laboratory results are available at the county level for many land uses, and these data may provide some indicators of nutrient status across the state. It should be noted, that soil test data are neither random nor representative of any particular county and may or may not be spatially representative or even comparable from year to year. Individuals may have their soil tested for many reasons, including concern over nutrient accumulation, productivity, and regulatory requirements. Therefore, it is inappropriate to make specific conclusions given this sort of data collection (J. Balasko, personal communications, 2006). However, state soil test lab results can be a good general indicator of overall soil P conditions or trends.

Soil test data at the state level from 1987 to 2004 indicate overall soil test P (STP) levels at 28 mg/Kg (56 lbs per acre) for grass-pasture agricultural fields, and 45 mg/Kg (91 lbs per acre) for grain corn-corn silage agricultural fields (Table 1.1). The highest STP levels among all counties from 1987 to 2004 in tall grass hay or pastures with less than 30% legume were in Grant, Hardy, and Pendleton Counties. Grant, Hardy, and Pendleton Counties were among the five highest counties for STP levels in corn grain fields (WVU Soil Testing Laboratory Soil test data 1986-2004). These data support the idea that if P accumulation has occurred in West Virginia, it is likely to have occurred in these counties. It is interesting to note that the counties with the higher STP levels coincide with the counties with elevated food animal production.

Phosphorus Mass Balance

The analysis of P inputs and P removal can be used to generate a P mass balance expression. Survey data, commercial fertilizer sales, and crop and animal production data can be used to track regional trends over time. When manure P additions minus crop P removal yield a positive P mass balance (Table 1.2) it could be an indication of P accumulation (Mid-Atlantic Regional Water Program, 2005). Row crop production areas only receive a portion of the animal wastes in this region. The higher the animal numbers and higher soil test P data, is consistent with the P mass balance data. While mass balance expressions for hay and pasture in West Virginia are unavailable, higher pasture/grass hay acreages and decreased removal mechanisms, make a positive mass balance likely if pasture and grass hay acreages receive similar manure applications.

Research Rationale and Objectives

Given the concentration of poultry houses and beef cattle, the associated animal manure, the current land use, the soil test data, and the P mass balance data, three counties (Grant, Hardy, and Pendleton) attract your attention when discussing P in West Virginia. If any counties in West Virginia are prone to P accumulation, it is likely to be one of these counties. The current research on the preferential movement of sorbing (P) and non-sorbing (chloride, bromide, and nitrate) components through soil profiles questions the traditional views of P immobility. Given the importance of P in the aquatic environment, limiting its movement into surface and ground water is paramount to building or maintaining a good working relationship between the agricultural and environmental communities. The extent that P could be moving through soil profiles in these counties needs to be addressed.

The objectives of this research were (i) to verify the presence of preferential flow in benchmark West Virginia soil series and (ii) measure soil test phosphorus (STP) levels within the preferential flow pathways and the surrounding soil matrix to determine the effects of preferential flow on phosphorus distribution within the soil profile. To that end, this research was conducted on benchmark soil series based on their frequency of occurrence under hay and grass pastures and recommendations of the West Virginia state soil scientist. Field experiments were conducted with dye applications to identify preferential flow. These stained profiles were photographed, sampled, and P levels were analyzed to determine if preferential flow had occurred and how it may have influenced P movement.

Hypotheses

Preferential flow can be identified in most of the soils under grasslands in eastern West Virginia. P is translocated within the preferential flow pathways bypassing portions of the soil matrix leading to elevated STP levels in close proximity to the preferential flow pathways.

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Figures and Tables

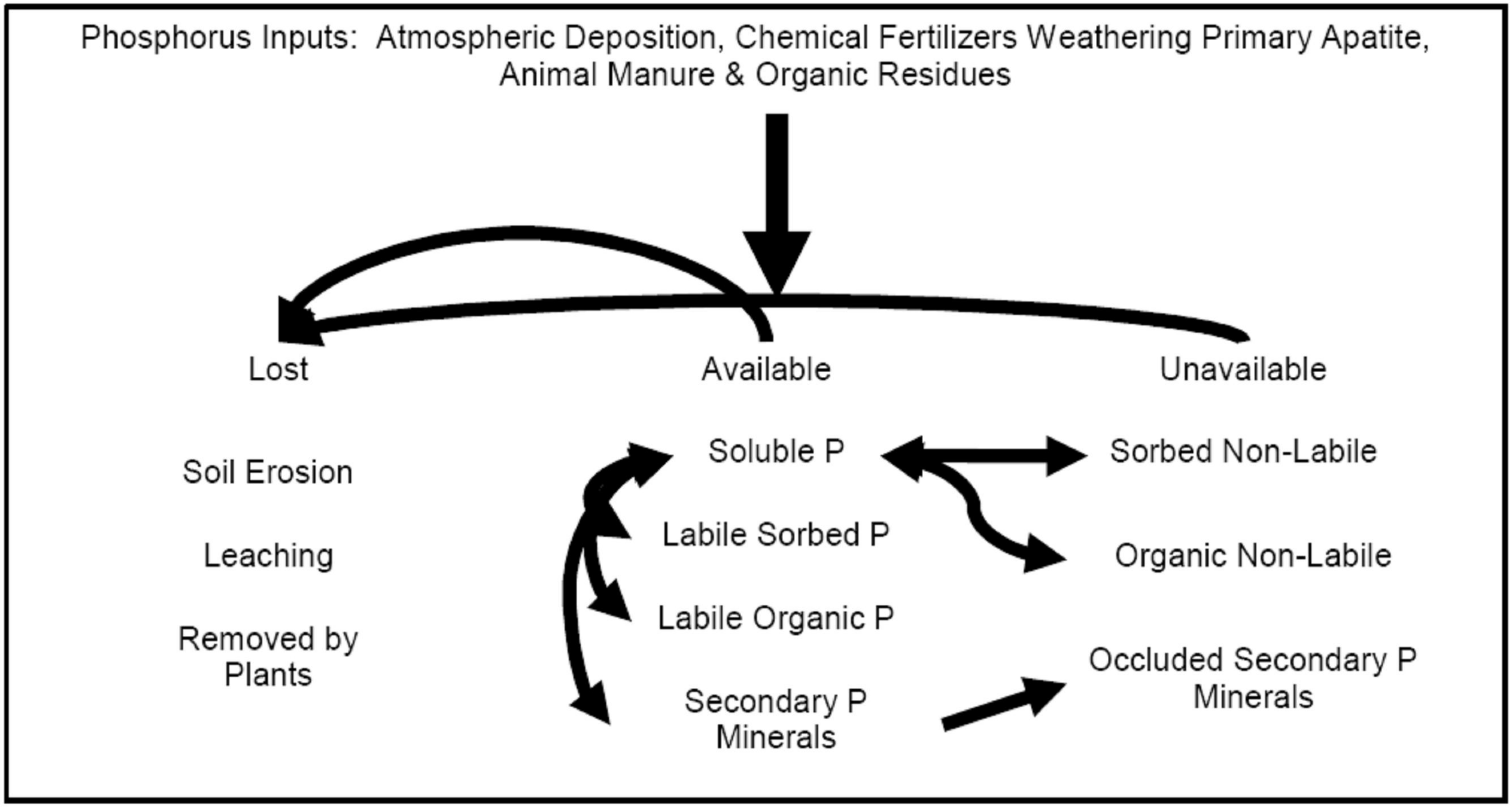

Figure 1. 1 Phosphorus fate and transport in soil: One directional line indicates input or removal of P while bidirectional lines indicate movement in each direction

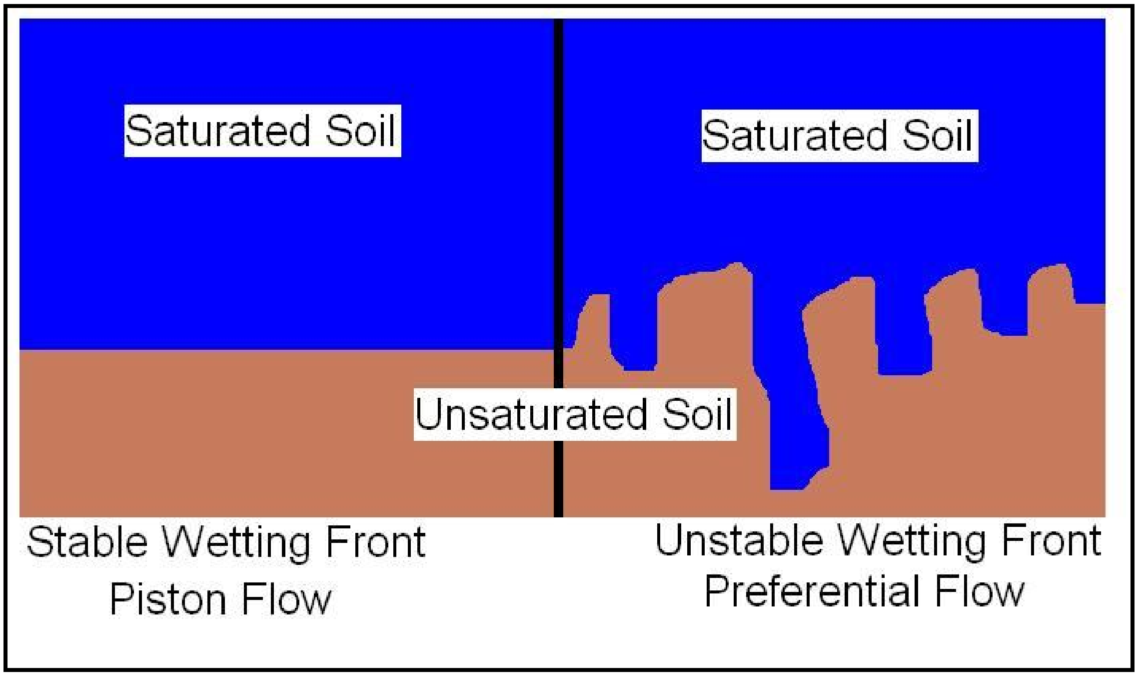

Figure 1. 2 A stable parallel wetting front ~ piston or piston like flow
An unstable wetting front ~ preferential flow

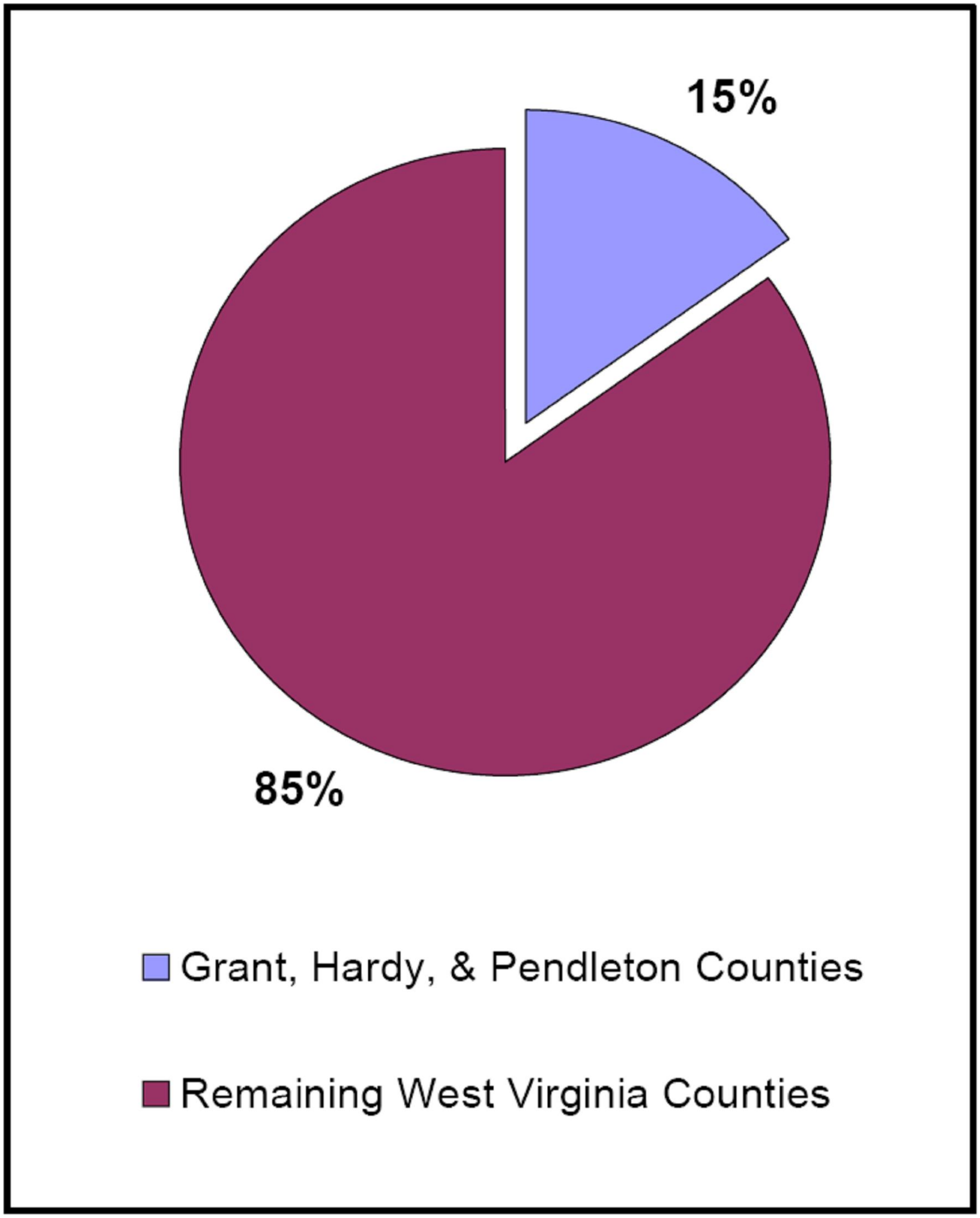

Figure 1. 3 West Virginia cattle sales (NASS, 2002)

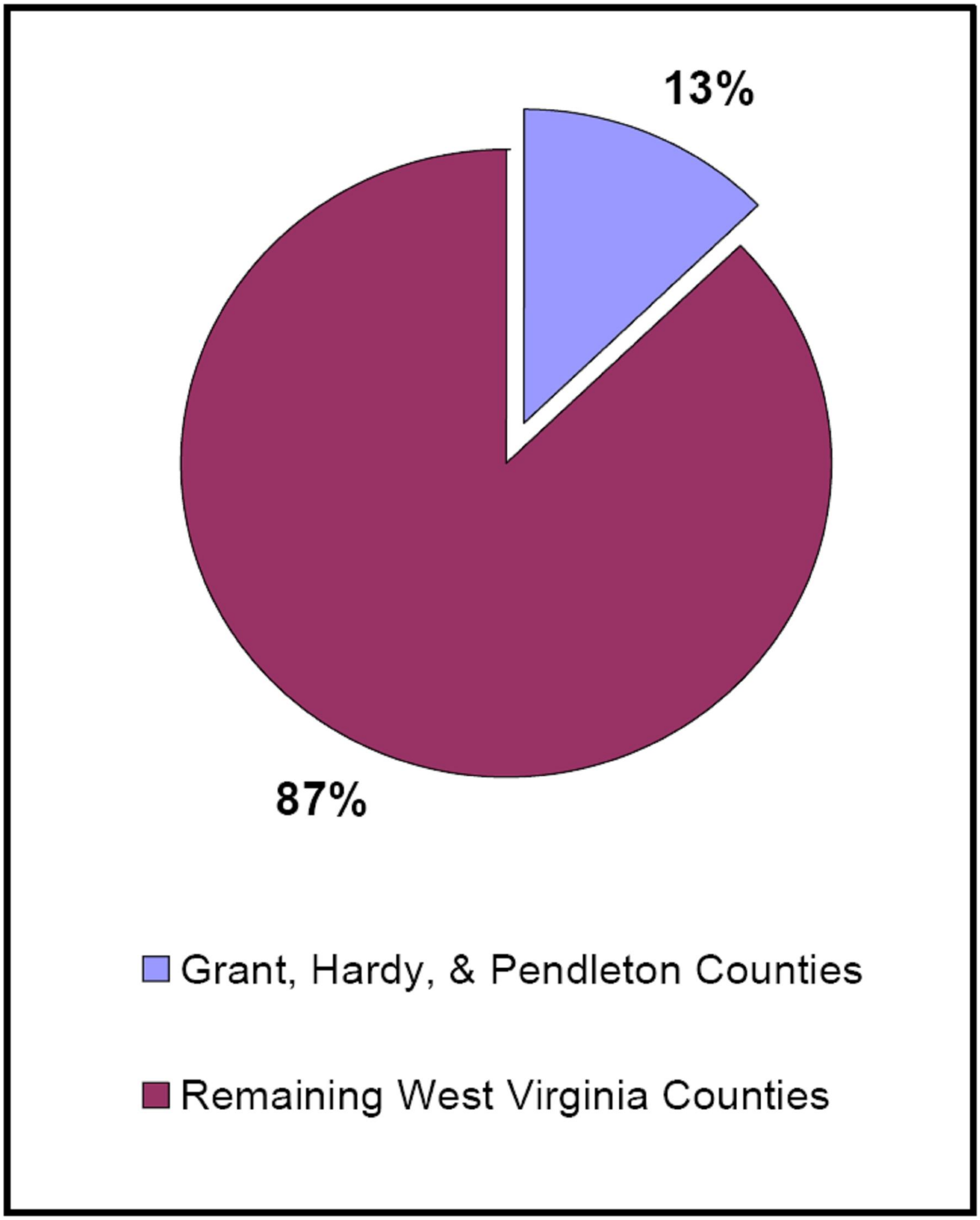

Figure 1. 4 West Virginia broiler sales (NASS, 2002)

Table 1. 1 Average STP levels by selected land use from 1986 through 2004

Field Type	Sample #	Average lbs P per Acre
Grass-Pasture	60979	58
Grain Corn-Corn Silage	14680	91

(WVU Soil Testing Laboratory Summary Results -- 1986 to 2004)

http://www.caf.wvu.edu/plsc/soilslab/000begin2.htm

Table 1. 2 P mass balance, applied manure P minus P removed by crop production (Mid-Atlantic Regional Water Program, 2005).

	year					
	1978	1982	1987	1992	1997	2002
	tons					
Grant County	414	479	565	731	834	959
Hardy County	318	384	471	765	1002	1114
Pendleton County	130	131	143	238	301	309

CHAPTER 2: PREFERENTIAL FLOW IN PASTURES ON BENCHMARK SOILS IN WEST VIRGINIA SOILS

Abstract

Preferential flow is a mechanistic description of irregular water movement in a soil profile where part of the soil matrix is bypassed during periods of infiltration and percolation. While a common phenomena, there is little research specific to West Virginia pasture soils. To identify the active preferential flow pathways, a solution of FD&C Blue #1 powder dye and water was applied in a ponding application to 24 pedons representing three different soil series. Sites were excavated two days after the application of dye to reveal the flow paths. Digital images of the dye stained soil profiles were taken to identify the active infiltration pathways. These images were examined to determine if the movement of the dye appeared to be preferential or piston like. A paired t-test was used to compare the stained areas of dependent horizons within each plot to determine if the horizons were statistically different or similar. Statistically different percent stained areas in dependent horizons were inconsistent with piston flow. Dye staining patterns were inconsistent with piston flow. Analysis of the collected images suggests that preferential flow occurred in each plot of each location of each series. Irregular wetting fronts, statistically different stained percentages between dependent horizons, and preferential flow like characteristics were present in the Berks, Buchanan, and Clarksburg series.

Introduction

For nearly 100 years, the scientific community has known that water flow in soils can be uniform or non-uniform (Hendrickx and Flury, 2001). In soil water movement, there are two major mechanistic models -matrix flow and preferential flow- and they have very different impacts on water flow and chemical leaching potential (Hendrickx and Flury, 2001). Matrix or piston flow is a stable sharp wetting front (Fig. 1.2) parallel to the soil surface as water moves downward through the soil profile (Djodjic, 2001). An irregular wetting front or unstable flow, can lead to more rapid movement of water in some areas or preferential flow (Bundt et al., 2001). Uniform water movement through a soil profile is matrix or piston flow and the rapid movement of water through pathways such as macropores, cracks, and wormholes is referred to as preferential flow (Djodjic, 2001).

Preferential flow can occur in many situations and conditions. Preferential flow paths can be the product of interaggregate pores, earthworm burrows, gopher holes, cracks, decayed root channels, and other types of macro-porous structures (Nielsen et al., 1986). These interconnected macropore pathways can contribute to soil water and nutrient loss and an uneven distribution of soil water and nutrients within the soil matrix (Booltink and Bouma, 1991). Steenhuis and Parlange (1991) found macropore flow in some instances to be of a greater significance in transport than matrix flow. In agricultural soils, preferential flow can be quite common (Petersen et al., 1997).

Dye tracing experiments are a common method used to identify the spatial patterns of water movement (Morris and Mooney, 2004), and can generate qualitative information about preferential and non-preferential flow (German-Heins and Flury, 2000; Weiler and Nae, 2003). Other methods of identifying or investigating preferential flow and nutrient leaching include chemical tracers, or measuring chemical constituents in leachate and TDR. Lee et al. (2001) used tracers and determined it was feasible to use a vertical TDR method to delineate preferential water and solute transport in soil. Brye et al. (2002) found elevated nutrient levels in leachate collected with soil tension lysimeters in a restored tall grass prairie and under corn production, and suggested that a significant portion of the nutrients measured in the samples were moving within preferential flow paths. The P levels in the leachate at various depths did not correlate with water soluble soil test P levels at those sampling depths thus suggesting the levels were related to the surface applications of P sources and the subsequent bypass of the majority of the soil matrix via preferential flow. Shipitalo and Gibbs (2000) applied dye tracers to biopores and verified flow into tile drains within 14 minutes, when soil series permeability ratings suggested it should have taken at least 12 hours.

Hatfield et al. (1997) examined a Woodbridge soil (Coarse-loamy, mixed, active, mesic Aquic Dystrudepts) (Soil Survey Staff, 2004) and found higher volumetric flow rates and shorter time to peak concentration levels of the applied tracers in intact soil columns as compared to packed columns. This is consistent with structured soils moving water through their profile faster than structureless soils. These results also suggest that intact soil columns should be used when studying solute transport in the lab in as much as they are more analogous with field conditions.

Kissel et al. (1973) examined a Houston Black (Fine, smectitic, thermic Udic Haplusterts) (Soil Survey Staff, 2004) and noted the movement of applied chloride corresponded with preferential movement of previously applied fluorescein dye. The larger continuous soil pores proved to be important pathways for the movement of Cl^- in the saturated swelling clays they examined. They concluded that much of the flow was occurring through limited areas at high velocities, and the movement of the Cl^- anion was by-passing the soil water within the surrounding soil.

Kulli et al. (2003) examined eight soils and measured the spatial distribution of the infiltration patterns to identify preferential flow. This analysis identified additional layers or horizons not identified in the field. The use of cluster analysis proved useful in identifying horizons and in identifying areas of preferential flow. Overall, soil horizons have a strong impact on water movement and many changes in texture were reflected in the dye infiltration patterns.

These studies demonstrate that there is no single method to conduct tracer and dye experiments. The concepts have been applied in many different ways and in conjunction with many techniques. For example, Hatfield et al. (1997) used dye tracers in intact and packed soil columns. Kissel et al. (1973) measured Cl and fluorescein from ponding applications, which lasted 1.5 days.

Kulli et al. (2003) conducted research in the field with dye tracers using a non-ponding (sprinkling) application.

Given the importance of nutrient enrichment in surface waters, research on preferential flow is needed. The management implications of preferential flow could impact from how much or how often a soil is fertilized and could provide better estimates of the environmental risk associated with a given soil. Simply knowing if certain soils exhibit preferential flow under any conditions is the first question that should be answered. If a soil exhibits little or no preferential flow, the additional risk of nutrient loss or uneven distribution is minimized, and the idea of a vast reservoir of P sorption sites in the subsoil available to acquire any lost P becomes more realistic. If a soil does exhibit preferential flow, it is possible the assumptions used in the present decision making process were incorrect, and some locations could pose additional unknown risks. The objective of this research is to identify if there are active preferential flow paths within the soil profile of selected.

Hypothesis

Ponded dye applications will identify preferential flow, in a wide range of soils found commonly under grasslands in eastern West Virginia.

Materials and Methods

Series and Location Selection

Given the lack of published data on preferential flow in naturally drained pasture soils of West Virginia, the extent, taxonomic significance, and local importance of benchmark soils make them ideal for comparisons to other series.

As such, benchmark series were selected from the most common series under grass and hay management schemes in Grant, Hardy, and Pendleton Counties, the three West Virginia counties that produce 87% of the broiler sales and 15% of the cattle sales (NASS, 2002). The selection was made by combining published soils series map data and published land cover data to rank the abundance of series under the land uses of interest. The presence of important or unique soil morphological features (e.g., fragipans, shallow bedrock, high rock fragment content, and differences in mineralogy) was also considered so there would be diversity and contrast among the benchmark series selected.

These series were selected based on availability of cooperative landowners. Specific locations for each series were chosen on farms which utilized primarily animal manure for fertilizers over the previous decade, and were currently used as hay or grass pasture fields. The specific plots within the locations were chosen based on topography (areas < 10% slope), with potential locations identified from published soil survey maps. These locations were excavated with an auger and compared to the official series description to determine if the locations was likely the series of interest.

Three benchmark soils series that are of large extent in eastern West Virginia were selected for this study: Berks (Loamy-skeletal, mixed, active, mesic Dystrudepts), Buchanan (Fine-loamy, mixed, semiactive, mesic Aquic Fragiudults), and Clarksburg (Fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs) . Berks occurs to the greatest extent under grassland and hay pasture land uses in Grant, Hardy, and Pendleton counties and is characterized by high rock fragments contents and moderately deep depths to bedrock. Buchanan and Clarksburg have fragipans but Clarksburg soils have relatively higher base saturations values associated with parent materials with more limestone influence. The Buchanan and Clarksburg series are less rocky than Berks, and are among the top 25 series in terms of extent under grassland and hay pasture land uses in Grant, Hardy, and Pendleton counties. The differences in soil morphological and chemical properties may influence water movement.

Experimental Design

The experimental design (Fig. 2.2) was a three stage nested design (Dowdy et al., 2004). Field experiments were conducted at two locations per selected benchmark soil series. At each location, two investigative plots were identified for study. In each investigative plot, two target applications of dye were made. This produced 24 target applications, with eight for each series. The target applications were arranged so they were approximately five to six feet apart in a paired arraignment to minimize the overall disturbance to the site. This facilitated the collection of percent dye staining per each cm of depth within each application from four to five images. At the plot scale, images were combined and to determine if the percent stained between a pair of neighboring horizons was significantly different, a paired t-test was performed. Additionally the image data was graphed to relate stained soil as a function of depth at the plot scale and a qualitative determination of preferential was made.

Dye Application

The positions of the investigative plots within a location were selected from locations between <10% slope, which facilitated a more even infiltration of the dye solution. Prior to dye application, the vegetation in the investigative plots was trimmed to an approximate height of 5 cm, and trimmed plant material was removed from the plot area.

Preferential flow pathways were identified in a fashion similar to the methods described by Flury et al. (1994). Flury et al. (1994) flood irrigated with a solution of Blue 1 at a concentration of 4 kg/m^3, using a total solution volume of 40 L/m^2. The dye was applied from a large sprinkling nozzle in less than one minute to a 1 m^2 infiltrometer ring driven into the soil to a depth of 20 cm. Ponding infiltration initiates the deeper, macropore flow component of preferential flow better than a slower simulated rainfall type application (Flury et al., 1994).

For this research, ponding of the dye on the soil surface on each one square meter target application was facilitated using reinforced steel containment apparatus of my design (Fig. 2.3). The containment apparatus were 1.3 m long, 1.3 m wide, and 0.3 m tall sheet metal frames that permitted controlled application the dye to the soil surface over an area larger than one square meter, thus limiting border affects. Along the bottom of each apparatus, the soil surface was opened with hand tools to form a slice that paralleled the bottom of the apparatus. Each apparatus was then pounded into the slice in the soil surface to an approximate depth of approximately 10 cm. The interface between the apparatus and the soil surface was sealed with a simple sodium bentenite mortar to limit leakage.

The dye used in this research was FD&C Brilliant Blue #1 powder (Blue 1). Blue 1 is a dark blue-purple powder and is used as a food additive primarily in beverages, bakery goods, dessert powders, candy, and confections. Blue 1 in solution is a brilliant greenish blue color. It is resistance to light and to heat. The chemical name Blue 1 is ethyl (4-{para [ethyl (meta-sulfobenzyl) amino]-a-(ortho-sulfophenyl) benzylidene}-2, 5- cyclohexadien-l-ylidene) (meta-sulfobenzyl) ammonium hydroxide inner salt, disodium salt (CCOHS, 1978). Dyes as tracers are commonly used in scientific investigation of subsurface flow, and Blue 1 is the most commonly used dye (Flury and Wai, 2003).

Each target application was flood irrigated with a solution of Blue 1 at a concentration of 4 kg/m^3. A total solution volume equal to 40 liters of dye solution per square meter of the containment apparatus area was applied from a storage container in approximately two minutes to facilitate near instantaneous ponding (Flury et al., 1994). Trimmed vegetative cover was left on the target applications to reduce the impact of the rapid application of the dye solution. The dye application was allowed to fully infiltrate the soil surface.

This method works well on flat surfaces. However, at greater slope gradients there is uneven distributing the dye. At steeper gradients the dye is redistributed in the containment apparatus becoming deeper at the lower end of the containment apparatus and shallower at the upper end. As a result, the depth of dye can be in excess of the targeted depth of 4 cm at the lower side of the containment apparatus and less than 4 cm at the upper side. Consequently, more dye was applied to the lower segments of the application area and less to others. Images were collected from multiple pit faces to minimize this effect. One application was sampled four to five times in the up slope direction. The other application was sampled four to five times in the down slope direction.

Excavation and Image Collection

Two to three days were allowed for the stained soil to partially dry after the application. Attempts to excavate on the day after application produced smearing of the dyed soil across each pit face. After the two to three day waiting period, a pit was excavated in each plot between the paired target applications. After initial excavation of the area between the paired target application areas, a full field description of the soil was performed using standard field methods (Schoeneberger et al., 2002). The % rock fragments, field textures, structures, colors, boundaries, motels, and redoximorphic features were described for each plot. In each target application, the central square was processed such that multiple images could be collected from a series of vertically exposed profiles within the central square meter of the target application (Flury et al., 1994). One of these vertically exposed soil profiles in the central square meter of a target application constitutes a pit face. Each pit face was prepared by digging away soil to create a uniform vertical profile. Loose materials, smears, smudges, or equipment marks were also removed prior to image capture.

A frame was constructed to facilitate the capture an image of each exposed profile (pit face). This frame provided a constant target of known dimensions to allow for proper processing of the images. The frame was constructed of Plexiglas cut into strips approximately 1.3 m by 10 cm wide.

These strips were joined with mechanical (bolts) and chemical (glue) fasteners to form a square frame whose open center exceeded a 1m x 1m square. Along the inner edge of the frame, holes were drilled into the Plexiglas to establish an outline of a one meter by one meter square and every decimeter break within each axis. Elastic strings were threaded in a grid pattern at 10 cm intervals within the (Fig. 2.4).

This framing grid was placed over each prepared pit face and a digital image of the soil profile was collected (Kulli et al., 2003). Pit faces were prepared and framing grids positioned to be as perpendicular as possible. The framing grid was positioned such that the top string corresponding to the top edge of the one meter by one-meter vertical square aligned with the soil surface. When excavated to less than the height of the framing grid, the framing grid was positioned as deep as possible.

Each pit face was photographed with the framing grid in place. Photographs were identified by their location, plot, application, and pit face. Two images were collected per pit face, one with flash, one without flash. When the position of the sun caused strong or pronounced shadows on the pit face was artificially shaded. All images were collected with a Cannon Power Shot S45 digital camera, with an image resolution of 2272 X 1704 pixels.

After collection of an image, new pit faces were established by cutting back the existing faces approximately 10 cm. A minimum of three and a maximum of five pit faces per target application were processed, depending on the presence of rocks, roots, obstructions, or collapses of the pit face

Image Processing

All images collected were digitally augmented and corrected with Corel Paint Shop Pro X (Corel Corporation, 2006)   Barrel distortions and rotational irregularities in the images were eliminated or reduced using corrective functions within the software used to process the images. The images collected were clipped to the known reference points on the framing grid. These corrected images were resized to the known measurements of the framing grid such that the pixel sizes in each image would correspond to an area of one millimeter by one millimeter on the actual pit face.

Red, green, and blue saturation levels were adjusted independently. The red saturation was reduced to the minimum levels to reduce the red-brown color of the unstained soil matrix. The green and blue saturations were increased to the maximum levels to highlight the greenish blue color of the dye in the soil profile. The images were split along the cyan, black, magenta, and yellow color planes. The cyan color plane appeared to best identify the dye stained areas in the images. The cyan plane image were saved in a JPEG format and renamed for additional processing. Each renamed image was reclassified, in a Boolean fashion such that stained pixels became values of one and unstained pixels the value of zero. This process made the percent stained pixels for each row equal to the mean pixel value of each row (Fig. 2.5). These values were combined as needed for the data analysis.

Image Analysis

The image data were analyzed by converting the pixel data into mean values for each cm depth interval across the entire 1 m width of each image and these were used to calculate the mean percent stained pixels for each horizon within a plot. The percent stained pixels within each genetic horizon were compared to the next horizon. To determine if a pair of neighboring horizons was significantly different, a paired t-test was performed. This test was repeated on each horizon and the ensuing horizon immediately below it (Fig. 2.6). To assist in a qualitative analysis of preferential flow the cm depth interval percent stained pixel data was plotted as a function of depth at the plot level (Flury et al., 1994) along with 95% confidence intervals. Statistically different stained pixels levels between multiple dependant horizon pairs could indicate preferential flow. When the function of dye staining with depth is considered along with the number and frequency of statistical difference between dependant horizon pairs a stronger qualitative determination of preferential flow can be made.

Results and Discussion

Berks

Berks is a common soil under pastures in eastern West Virginia. It is a moderately deep well drained benchmark series with rock fragments ranging from an low of 10-50% in the A or Ap horizon to as high as 90% in the C horizon (Soil Survey Staff, 2004). The sites proposed as Berks were shallow (38 to 60 cm to bedrock, and >64 cm to a fractured shale C2 horizon in L2P12, L2P11, L1P4 and L1P5 respectively (L=location number, P=plot number). Below the surface

Ap horizons at these sites, the soil ranged from very to extremely channery. The examination of the Berks sites indicated the proposed locations were likely Weikert (Loamy-skeletal, mixed, active, mesic Lithic Dystrudepts) in some of the investigative plots. The range of characteristics for Berks indicates a depth to bedrock between 20 and 40 inches, and if a Berks locations is less than 20 inches to bedrock, the soil is Weikert (Soil Survey Staff, 2004). Some pit faces in some plots lacked the minimum depth of 20 inches to the R horizon (Table 2.1). Profile descriptions for research plots can be found in Appendix 1.

With these locations, there was a problem in determining the presence of lithic or paralithic materials. The shale bedrock under these plots was fractured. The frequency of these fractures is less than 10cm and that was too close together to be considered lithic or paralithic materials, therefore taxonomic criteria indicate that the shale at these sites should not be considered lithic materials. Despite the fact that rock fragment content was greater than 80% within 20 inches of the surface in three of four plots and greater than 70% within 20 inches of the surface in all plots; there were no lithic contacts as defined taxonomically. While there was not sufficient data collected to fully classify these soils, these soils are more representative of Weikert, another benchmark soil commonly associated with Berks in these landscapes.

There were 37 images collected for Berks. The nested design generated 10 images for each plot, five from each dye application, for 20 images per location. All 20 images were collected at Berks L1P4 and L1P5. At Berks L2P11 and L2P12 there were 17 total images collected, five from one of the dye applications and four each from the other three. Images were combined for analysis at the plot scale by calculating the mean percent stained value for each cm of depth.

When the percent stained area was calculated and graphed for each plot, there were similarities within each location, but the graphs were very different between each location. For Berks L1P4 and L1P5, the plots indicated a roughly linear decline with depth (Fig. 2.7). For Berks L2P11 and L2P12, the plots indicated an exponential decline with depth (Fig. 2.8). This rapid decline in staining at the surface and more gradual decline through the subsoil was not unique to Berks L2. At Berks L1, below the Ap-Bw boundary, the decrease in percent staining per unit depth declines before reverting to a decrease in percent staining per unit depth similar to that in the Ap horizon. At Berks L2 the decrease in staining stops in the upper portion of the Bw horizon and the percent stained area remains between seven to ten percent.

Each location has a similar distribution of rock fragments within the profile. The percent rock fragments start around 20% and increase to around 80% in each location (Table 2.1). Overall Berks L2 has more rock fragments in one of the surface horizons and both C horizons. These locations have similar textures as well. There it is possible that there could be a management issues that led to this difference. Perhaps Berks L2 has lower stocking rates of cattle or less farm traffic such as trucks and tractors. Berks L1, has been planted in corn as recently as 25 years ago, and may have higher stocking rates of cattle when used as pasture. It is possible higher stocking rates could have led to surface compaction and limited the near surface interconnectivity of the macropore network (Dreccer and Lavado, 1993). Given the shallowness of these plots, and the platy structure (Table 2.1) in the surface horizons of Berks L2P11 and L2P12 it is possible the only downward movement of the dye was in large continuous macropores that drained to the fracture network within the shale bedrock (Fig. 2.8).

The paired t-test yielded p values of <0.1 in 70% of the horizon pairs and values of <0.05 in 60% of the pairs indicating a significant increases or decreases in percent stain between many horizons and possibly a change in flow characteristics between some horizons (Table 2.1). There were differences in texture or structure or rock fragments between many of the horizon pairs with significant differences in percent stained pixels. In some instances there were differences in texture or structure or rock fragments and the percent stained values in a horizon pair and there were no significantly different. The horizons with p values of >0.1 were all subsurface horizons in Berks L2P11 and L2P12 indicating more similar percent stained values between horizons with depth. These were the plots with an exponential shaped relationship between the percent stained pixels and depth. In addition, the horizons in question were the subsurface horizons where the percent stained pixels remained more or less constant within the exponential shaped function. The surface horizons above these horizons were platy in structure. It is possible the platy structure may have cause lateral movement of dye solution in the Ap horizons and only allowed downward movement of the dye in macropores which reached into this horizon.

This could generate a more consistent downward movement in a limited portion of the horizon (Table 2.1).

Buchanan

Field examination of the Buchanan locations exhibited characteristics that were for the most part, consistent with the range expected for this series. Buchanan is a very deep, and somewhat poorly to moderately well drained soil with a depth to bedrock between 5 and 20 feet or more. The depth to fragipan ranges from 20-36 inches in Buchanan. The textures of the Bt horizons could include silt loam, loam, clay loam, or sandy clay loam. The texture BE horizons range from silt loam to loam. The textures of Btx horizons could include silt loam, loam, clay loam and sandy clay loam (Soil Survey Staff, 2004). All Buchanan locations and plots were excavated beyond one meter in depth with all initial images covering one meter of profile depth. Overall, the proposed Buchanan locations were sandier than Berks or Clarksburg and were on the sandier side of the expected range of textures for Buchanan. Profile descriptions for all research plots can be seen in Appendix 1.

Images collected at these locations were cropped to the shallowest image within each plot. There were 40 images collected for Buchanan. Twenty images were collected per location. From each plot, 10 images were collected. In each plot, five images were collected from each dye application. The images were combined for analysis at the plot scale.

When the percent stained area was calculated and graphed for each plot, there were similarities within each location, but the graphs were significantly different between locations. Buchanan L1P1 and L1P2 produced a sigmoid shaped plot (Fig. 2.9). Buchanan L2P13 and L2P14 generated graphs with more linear depth function (Fig 2.10). At Buchanan L2P13 and L2P14 at a depth of approximately 50 cm, the decrease in percent stained pixels increase with depth. This portion of the plot is similar too the lower subsurface horizons of the exponentially shaped plots in the Berks series. A similar change is seen in L1P1 and L1P2.

The sigmoidal shape at Buchanan L1 can be explained by dye ponding on the top of the Bt1 and moving through the more similar Bt2 without impact, before flow becomes concentrated around the prismatic faces in the fragipan around a depth of 50 cm. The point where the decrease in percent stained pixels increase with depth at L2 does coincide with the fragipan. These fragipans appear to cause the percolation to become focused in limited locations. The data does not indicate the dye being restricted by the fragipan. No other specific tendencies in texture, structure, or rock fragments are associated with observed changes in the dye staining patterns.

For this soil, 82% of the horizon pairs in this series yielded a p value < 0.1 and over 76% were < 0.05 indicating a statistically significant increases or decreases in percent stain and possibly a change in flow characteristics between horizons. The Ap-Bt1 pair in L1P1 and the A-Ap pair in L1P2 were not significantly different (Table 2.2). The sigmoidal shape of the staining percentage graph relative to depth can create similar percent stain values between two horizons. As dye increase in one, it decreases in the other, and the mean across the horizons become similar. The other pairs which are above the p=0.05 threshold are horizon pairs in the fragipan. The image analysis in the fragipan horizons is consistent with the previous assessment that these fragipans appear to concentrate but not restricted the dye percolation, given the volume used.

Clarksburg

Clarksburg soils typically are very deep and moderately well drained. The depth to the fragipan in most Clarksburgs ranges from 20 to 36 inches. Depth to bedrock is greater than 60 inches. Texture of the Bt or BE horizons can include silty clay loam, silt loam, loam, and clay loam. Typically, the texture of the fragipan can include silty clay loam and clay loam (Soil Survey Staff, 2004).

The soils of the Clarksburg map units identified in this research were not consistent with the range of characteristics associated with the description of the Clarksburg series. These soils differ in terms of texture and depth to possible fragipan. For example, the Bt1 horizon in Clarksburg L1P8 was the proper texture, displayed prismatic structure parting to subangular blocky, but was to close to the surface and lacked the requisite brittleness. In Clarksburg L2 the Bt2 horizons were deep enough, but the clay content was too high, and while very dense and pan like, the horizon lacked the prismatic structure and requisite brittleness. Similar trends were described at all the Clarksburg map units investigated. As such, these horizons were labeled Bt horizons not Btx horizons. Profile descriptions for all research plots can be seen in Appendix 1.

In eastern West Virginia It is typical of Clarksburg map units to have a clayey subsoil that is dense, with firm or very firm consistence, may perch water, and is somewhat restrictive to root development, but has an absence of brittleness (J. Beard, personal communications, 2008). These “claypans” behave similarly to fragipans and from the standpoint of soil use and management, have limitations and interpretations consistent with the Clarksburg series. The soils examined in these Clarksburg map units are typical of the soils mapped as Clarksburg in Grant, Hardy, and Pendleton Counties (J. Beard, personal communications, 2008). You could argue that what ultimately matters is how the dye moves in soils that are mapped as a specific series relative to the soils in that general area. In this regard, these soils are very good matches to what we would expect to find mapped as Clarksburg on eastern West Virginia farms.

There were 40 images collected for Clarksburg. The nested design generated 10 images for each plot, five from each dye application, for 20 images per location. All 20 images were collected at Clarksburg L1P6 and L1P8. All 20 images were collected at Clarksburg L2P9 and L2P10. Images were combined for analysis at the plot scale.

When the percent stained area was calculated and graphed for each plot, there were similarities between plots within Clarksburg L2 and differences between the plots within Clarksburg L1. Overall, the plots of L1 and the plots of L2 were different from each other (Fig 2.11 and 2.12). L1P6 appeared to have a sigmoid like shape similar to the sigmoid shape seen in Buchanan L1P1 and L1P2 (Fig 2.9). The L1P8 data yielded a exponential like function similar to the graph of Berks L2P11 and L2P12 with the exception of the increasing trend near the surface seen in Berks L2P11 and L2P12 (Fig 2.8).

The inflection points in the graph of L1P6 occurred at the horizon boundaries of Bt horizons. As the dye entered the Bt1 horizon the platy structure may have caused lateral flow and concentrated the dye distribution into macropores. As the dye moved through the Bt2 with its prismatic structure it appears that it was restricted and ponded on top of the 2Bt3 horizon. The texture changes from clay loam to channery clay associated with this lithologic discontinuity could have caused soil water to be perched on top of the 2Bt3 horizon (Table 2.3) which would explain the shape of the graph (Fig. 2.11). The graph of L1P8 showed no visual relationship between the overall trend of the depth function and any morphological features.

Clarksburg L2P9 and L2P10 (Fig 2.12) data produced graphs that were more similar to the graphs of Berks L1P4 and L1P5 (Fig 2.7). At this location, the dye application received precipitation (rain) hours after the initial infiltration and removal of the containment apparatus. The duration was brief and the volume of rain was approximately 5 mm. It is possible this brief addition of un-ponded rainwater could have altered the staining near the soil surface, accounting for the increasing dye levels over the first few cm of depth if the rain washed or leached out the dye near the surface. Additionally, the A horizons were silt loam texture and the Bt1 horizons were silty clay loam and clay loam textures respectively. It is possible the transition in texture cause the dye to spread latterly and pond at that boundary.   There was also a subtle change in the slope of the curve below the Bt1 horizons that coincided with another change in texture to clay.

Approximately 93% of the horizon pairs at the Clarksburg sites exhibited statistically significant differences in staining percentages at the p=0.1 level, and nearly 86% the horizon pairs at the Clarksburg sites exhibited statistically significant differences in staining percentages at the p=0.05 level (Table 2.3). Among pairs which did not indicate significant differences the Bt1-Bt2 pair in L1P6 could be due to an increasing function changing to a decreasing function over similar ranges creates similar percent stained matrix values for each horizon. The other pair, Bt2-Bt3 from L2P9 has the same texture and structure and was significantly different at the p=0.1 level (Table 2.3).

Conclusions

Each series, exhibited at least one statistically different pair of horizons in every plot meaning that the percent stained pixels increased or decreased significantly from the overlying to the underlying horizon. When combined across all series, locations, and plots 76% of the total horizon pairs exhibited significant differences in percent stained pixels. The specific changes in patterns and the corresponding changes in horizons are likely due to changes of structure or texture that have lead to distinguishable horizons and distinguishable flow control characteristics.   However, the same changes in other horizon pairs yield no significant difference in staining percentage. The data suggests that when differences in staining percentage occur there are morphological differences that could explain the changes in staining percentages, but the presence of these features do not necessarily produce significantly different staining percentages.

If part of a profile exhibits preferential flow characteristics, some segment of the profile is potentially rendered unavailable for nutrient exchange and ecological sequestration of P. Conversely, if the tendencies toward a preferential flow behavior are sufficiently weak, the net impact on management could be less important. Given the diverse morphology of the selected series, the statistical difference in staining percentages, the possible association between horizonation, and the changes in the staining as a function of depth, it is far more likely that there is some degree of preferential flow in these series. This is consistent with the assertions of Flury et al., 1994 whose research indicated more often than not you will find preferential flow.

Matrix or piston like flow (Fig. 2.1) utilizes the entire soil matrix for sorption and exchange. Conversely preferential like flow is characterized by bypassing some portion of the soil matrix (Fig. 2.1), yielding deeper percolation. When the collected images are compared to these contrasting models the best fit is the preferential flow model.

Peterson et al. (1997) noted preferential flow was common in agricultural soils. Under conditions similar to those outlined in this research (flat, agricultural, grasslands, with histories of manure based fertilization) preferential flow appears to be very common as well. Flury et al. (1994) noted you would be more likely than not to find preferential flow in Swiss agricultural soils. In additional series, landforms, and management scenarios, the identification of preferential flow is probable in some series given the morphologic diversity of the series investigated in this research.

While additional data are needed for other soils in West Virginia, the influence of preferential flow in management decisions should be carefully considered. Preferential flow as an afterthought in a management framework fails to consider how likely preferential flow is. This research indicates some degree of preferential flow is likely in most agricultural environments similar to this study. Management models that conceptually do not mimic reality pose some unidentified risk.

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Figures and Tables

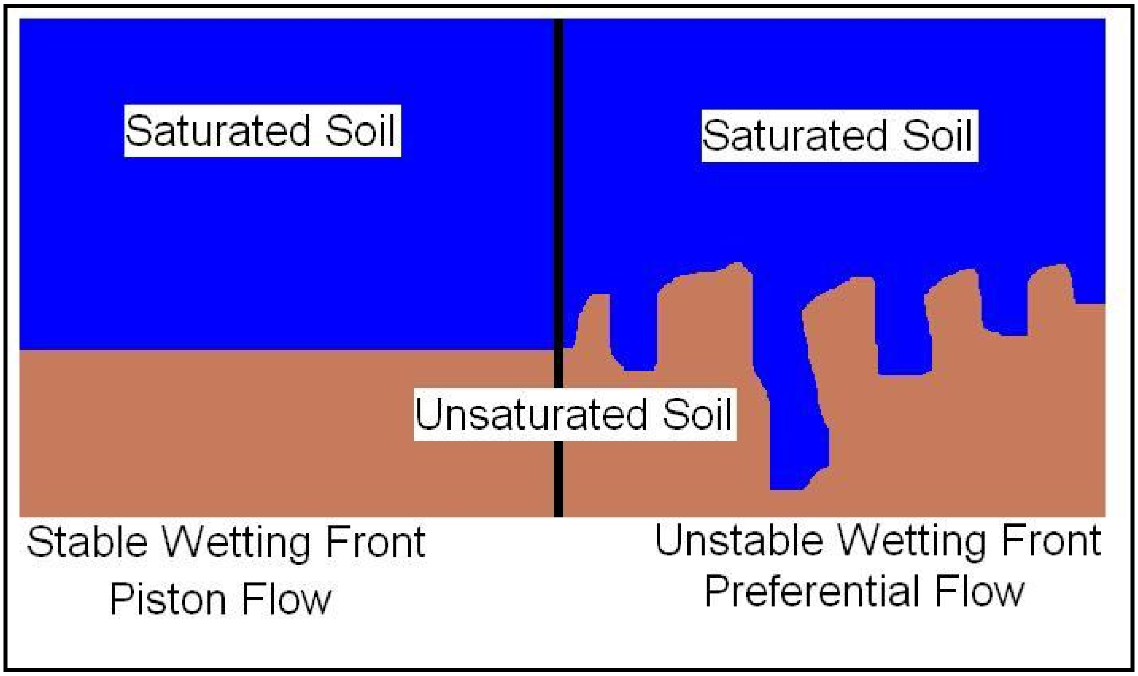

Figure 2. 1 A stable parallel wetting front ~ piston or piston like flow
An unstable wetting front ~ preferential flow

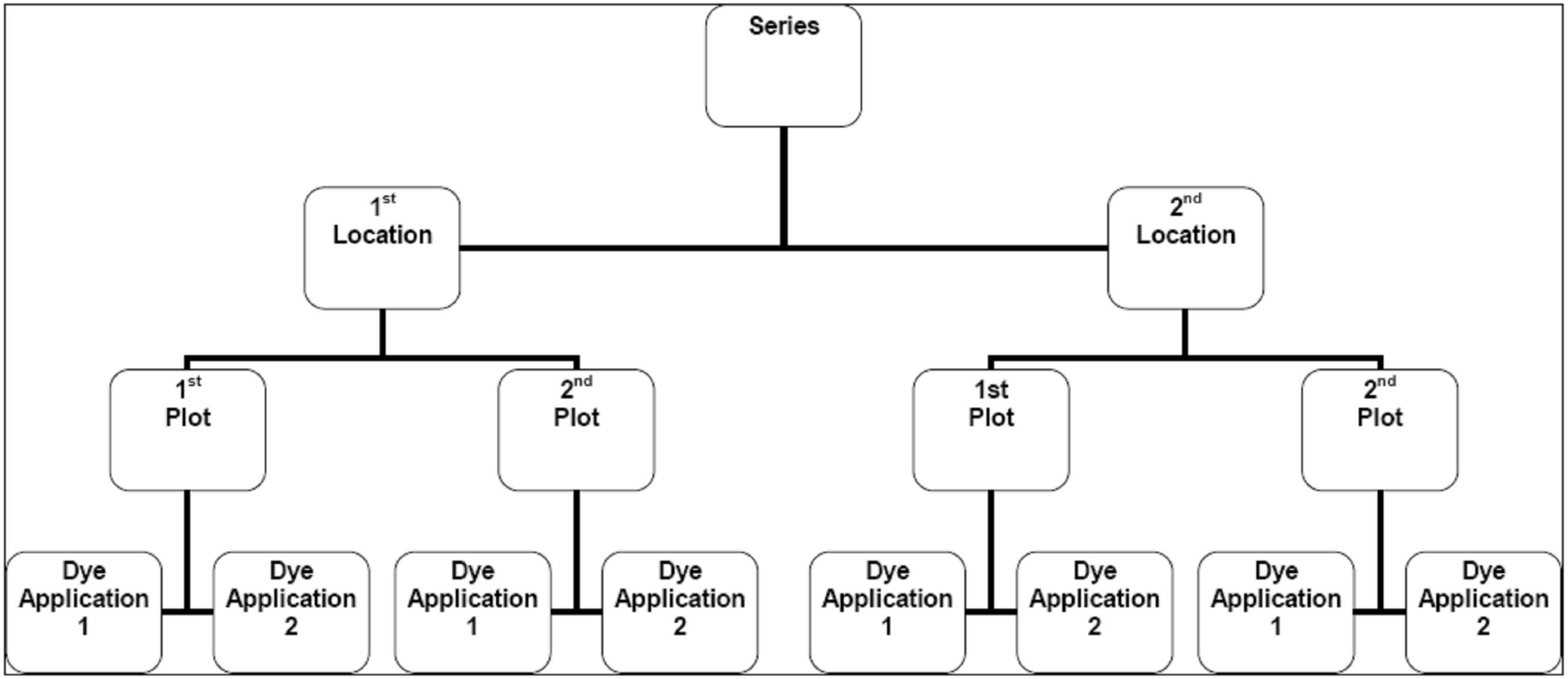

Figure 2. 2 Three stage nested design

There are two nested Locations within each series; there are two plots nested in each of location, and two dye application sites nested within each plot.

Figure 2. 3 Steel reinforced 1.3 meter by 1.3 meter dye containment apparatus used to facilitate dye ponding and infiltration

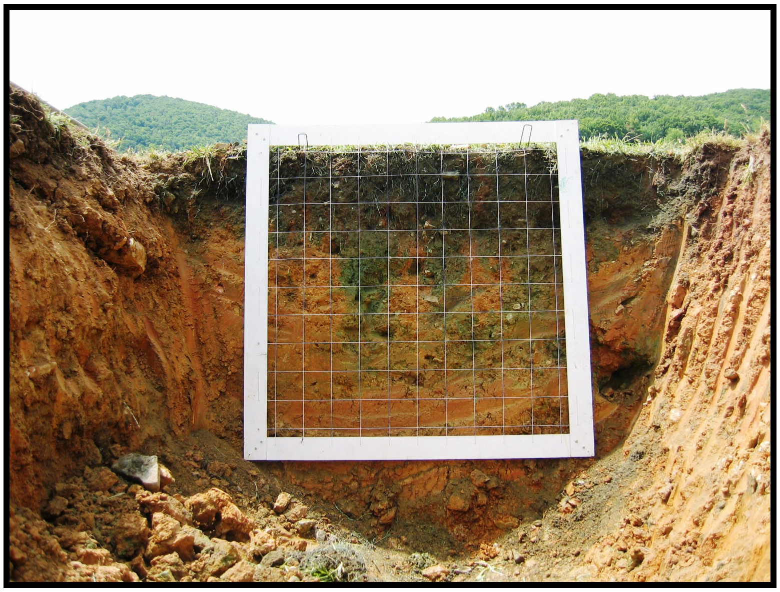

Figure 2. 4 One-meter elastic string grid framing grid for image referencing

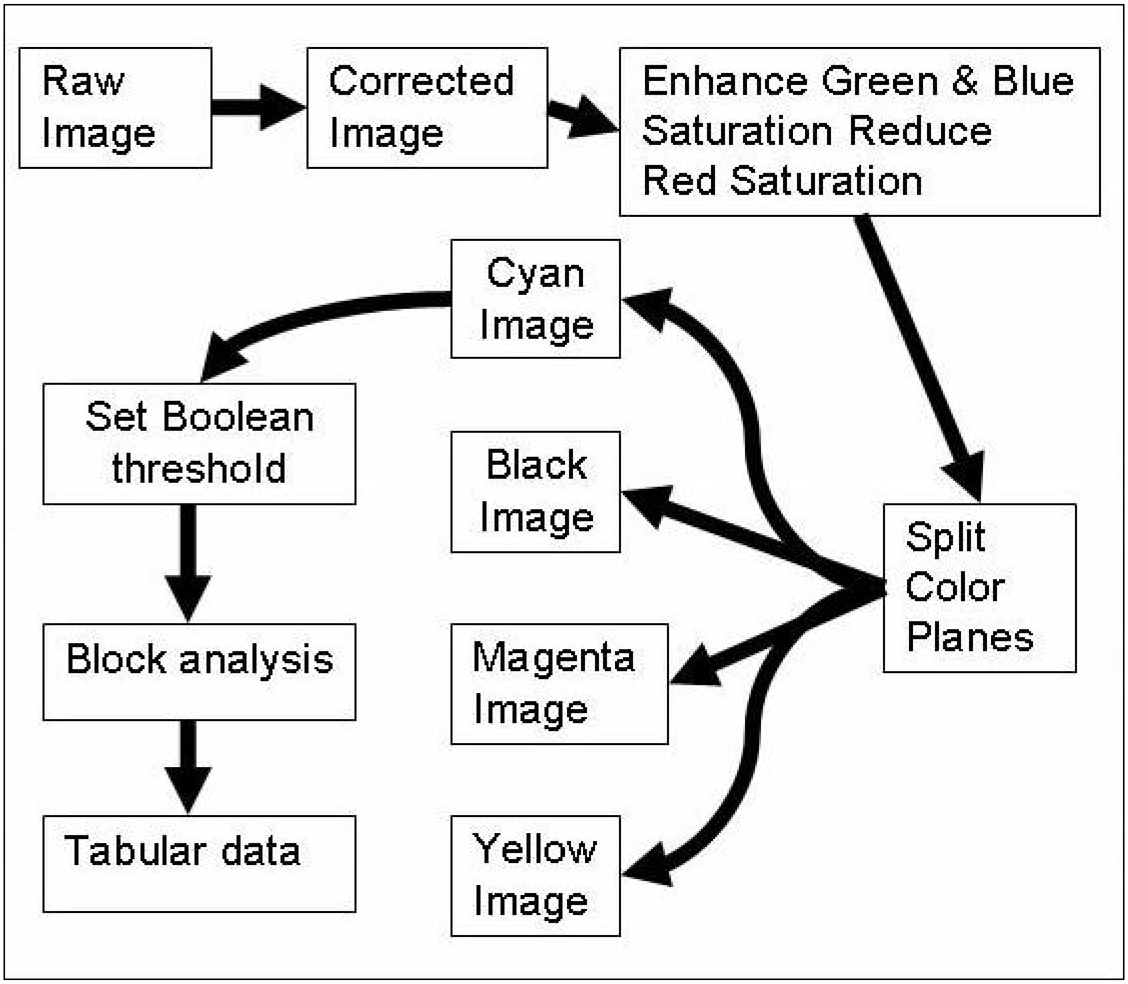

Figure 2. 5 Flow Chart of the process of converting a color digital image into tabular data for multiple forms of analysis of dye coverage in each horizon

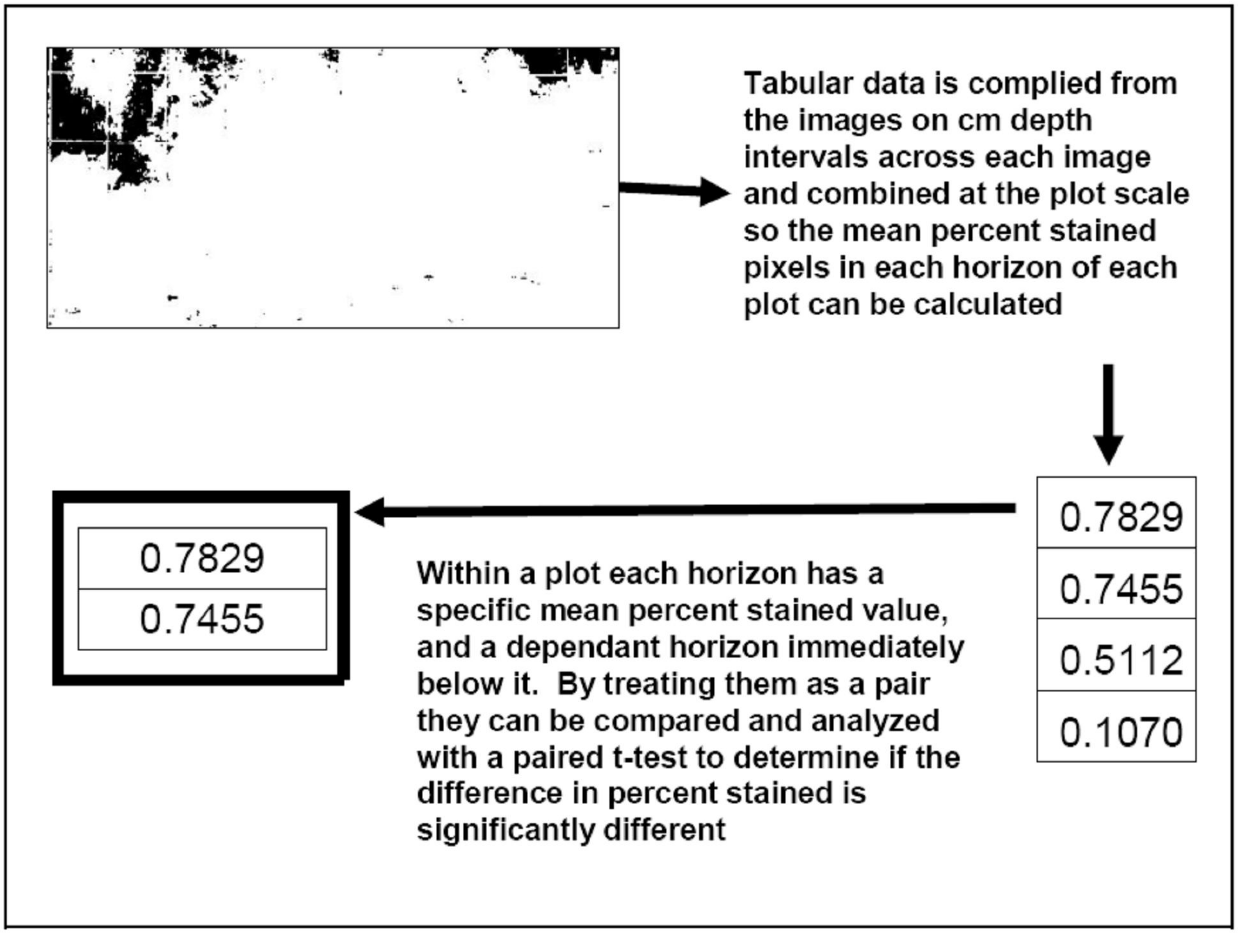

Figure 2. 6 Dependant horizon analysis with paired t-test

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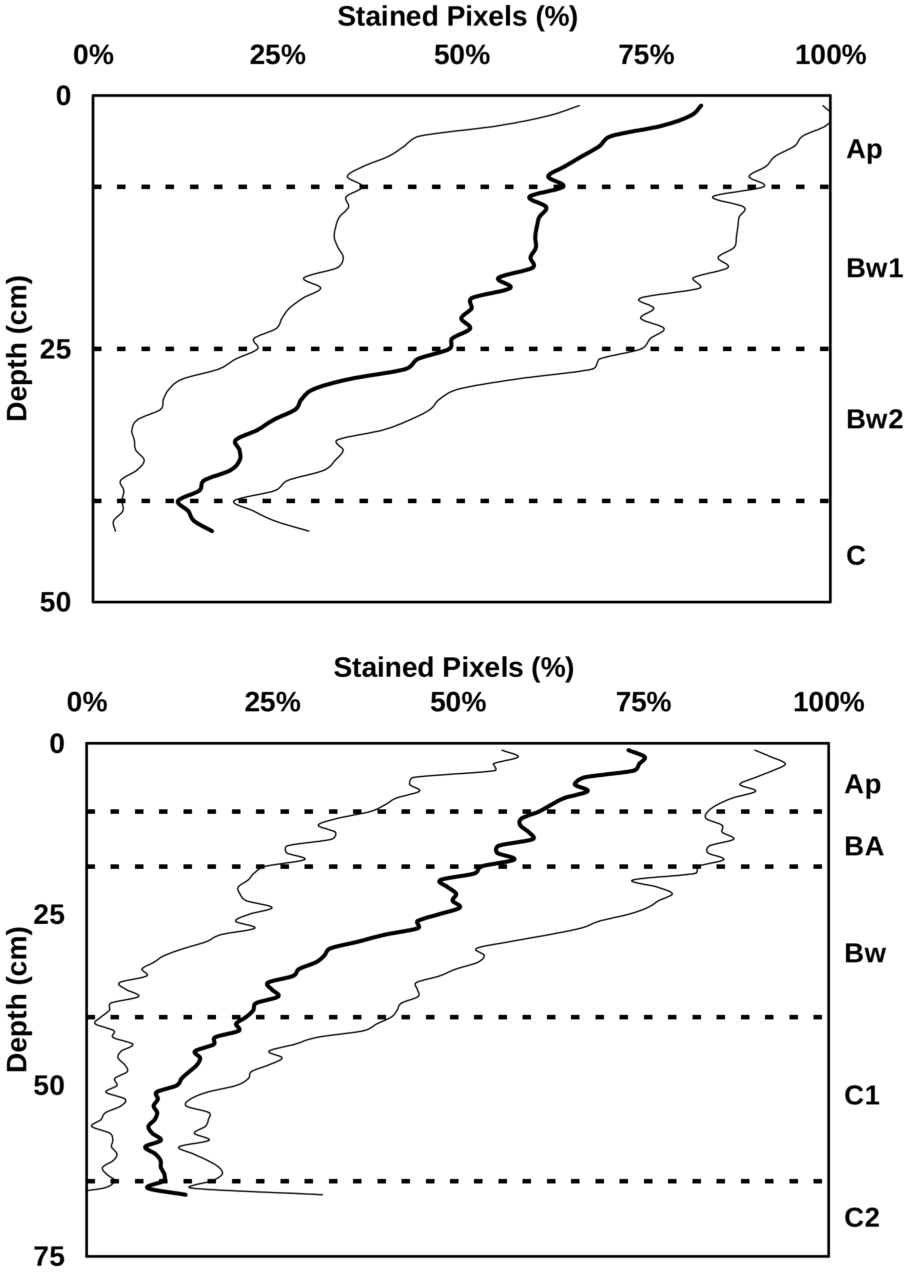


Figure 2. 7 Percent Dye Stained Matrix for Berks L1P4 (top) and L1P5 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries.

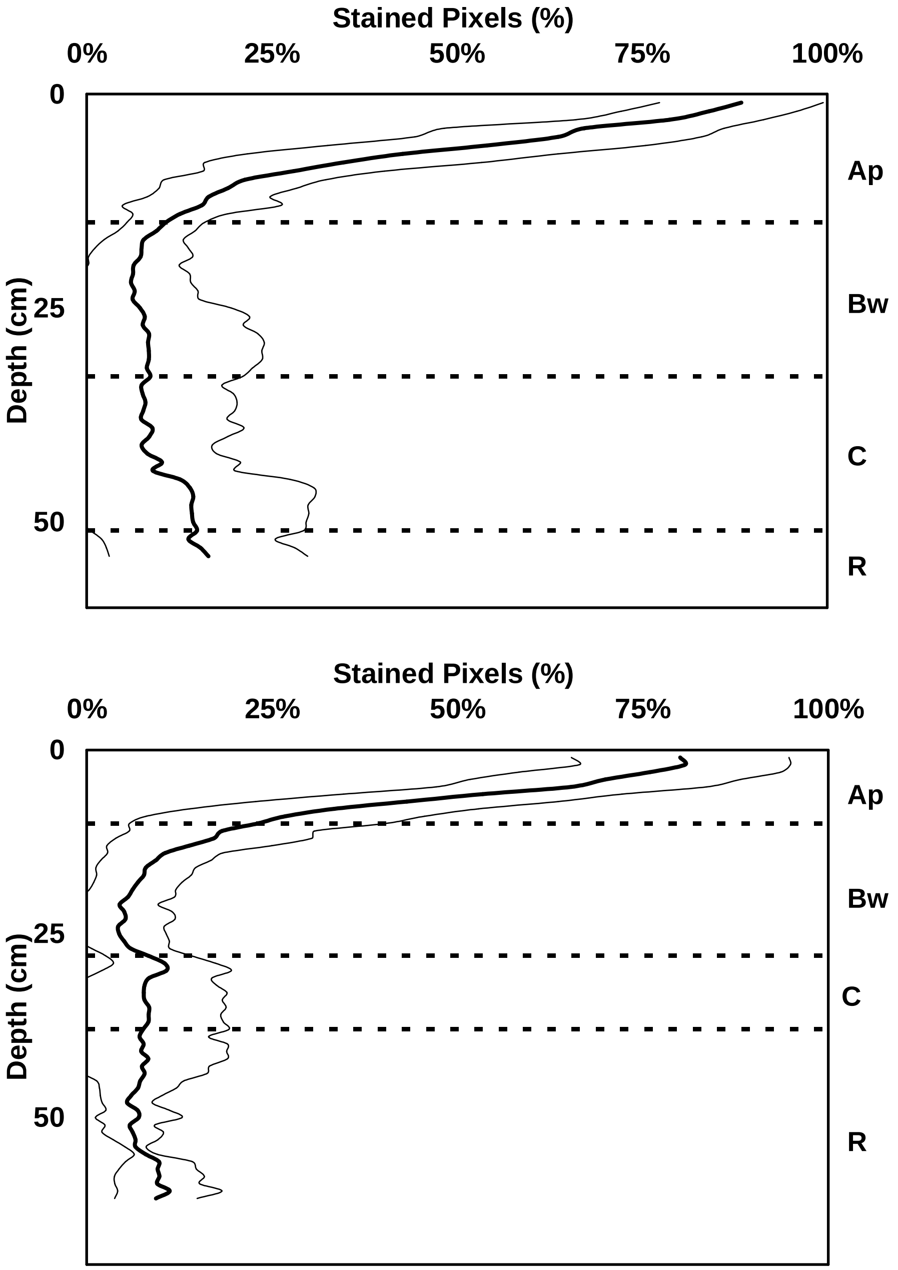
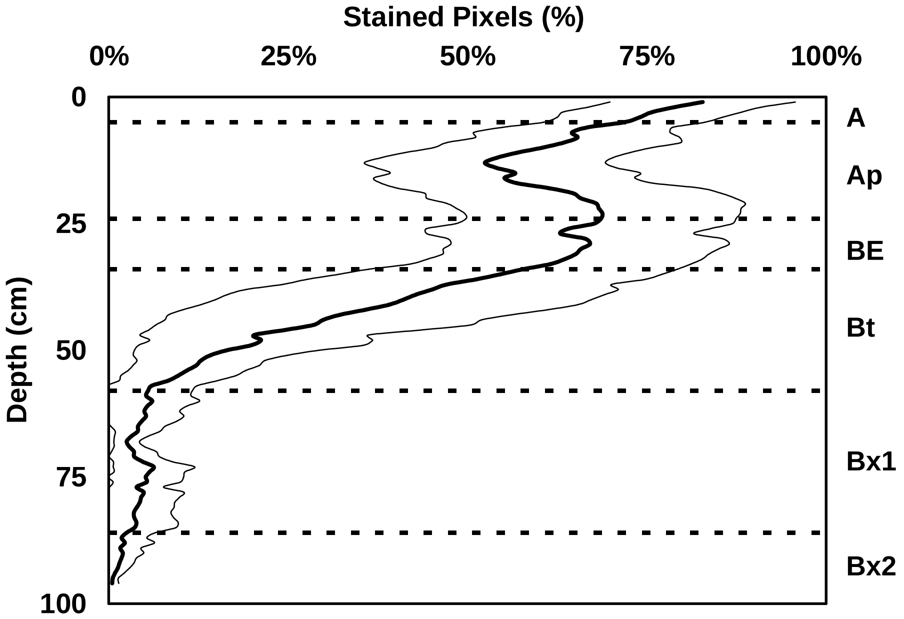


Figure 2. 8 Percent Dye Stained Matrix for Berks L2P11 (top) and L2P12 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries



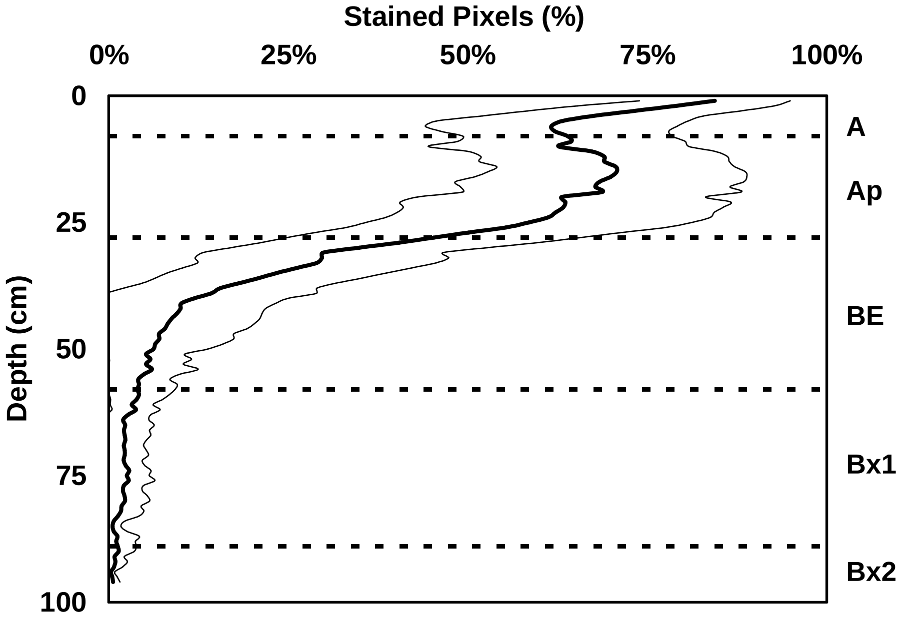


Figure 2. 9 Percent Dye Stained Matrix for Buchanan L1P1 (top) and L1P2 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries

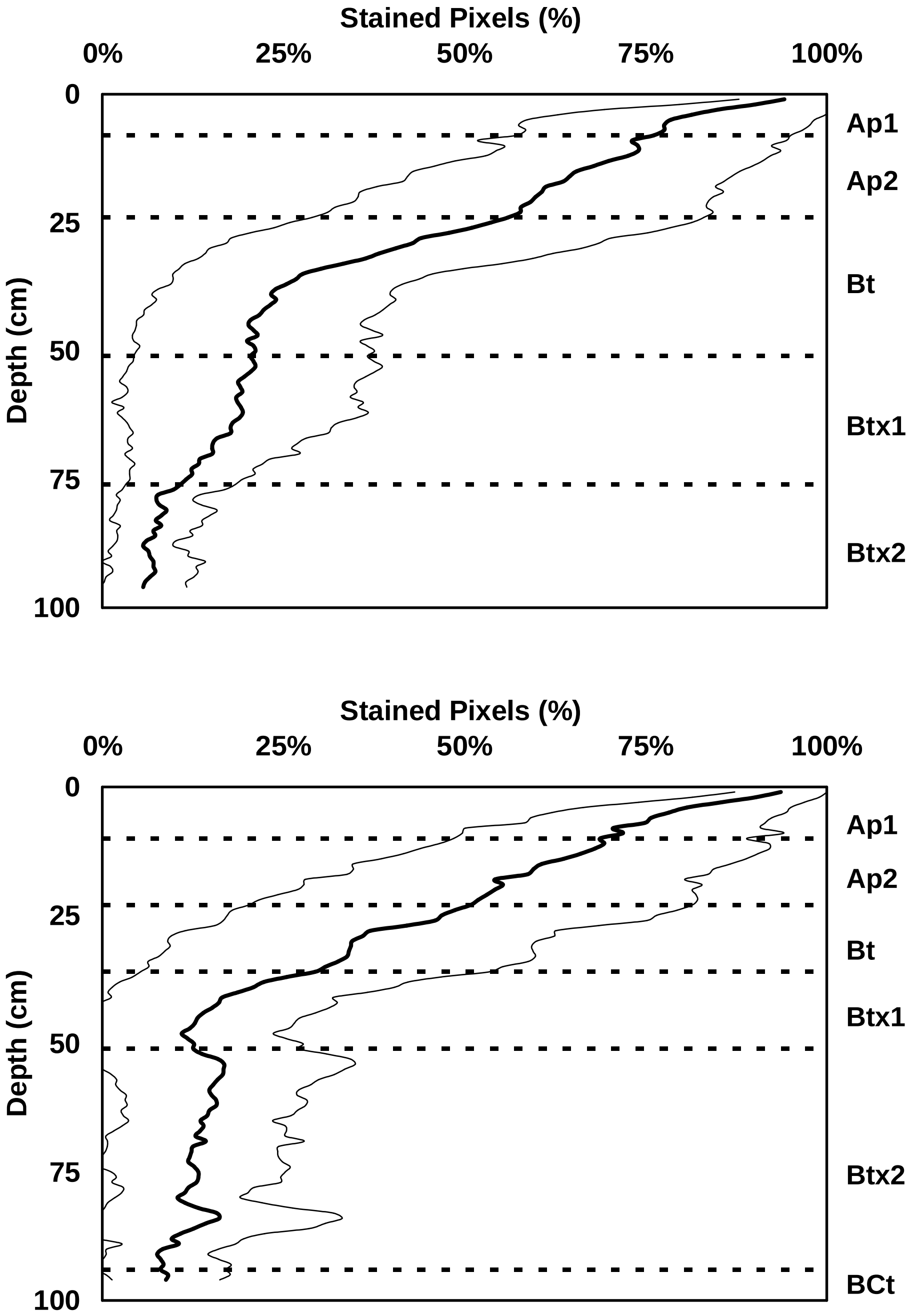


Figure 2. 10 Percent Dye Stained Matrix for Buchanan L2P13 (top) and L2P14 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries

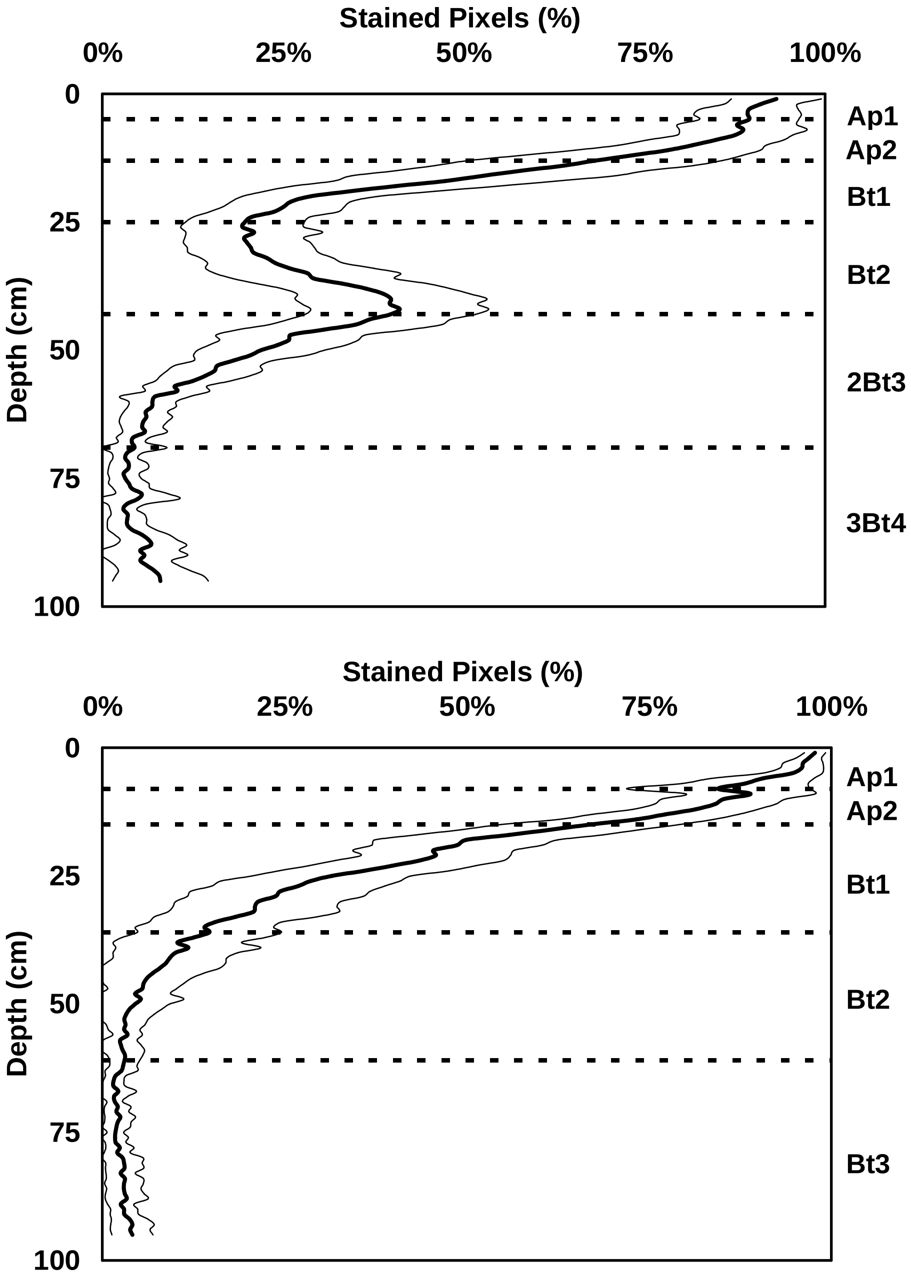


Figure 2. 11 Percent Dye Stained Matrix for Clarksburg L1P6 (top) and L1P8 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries

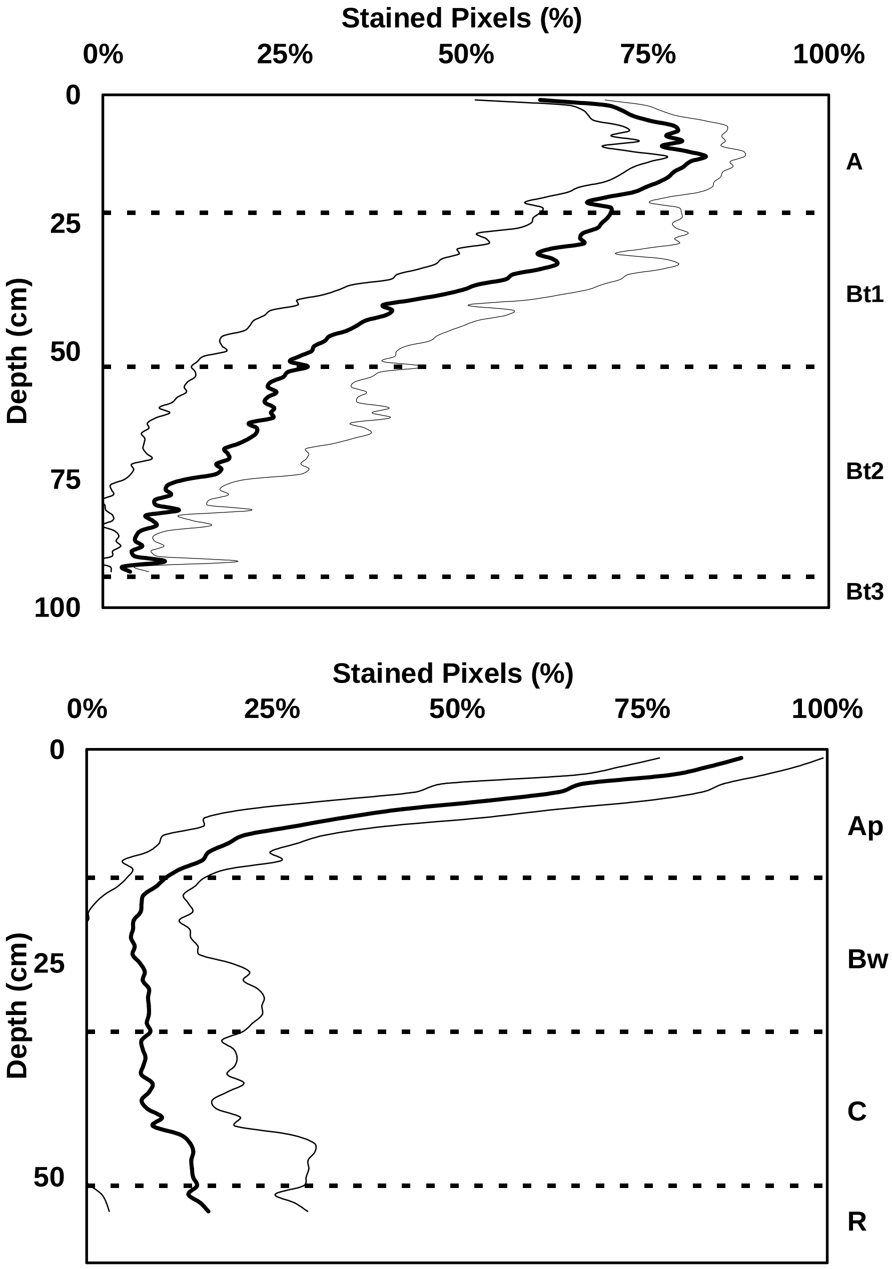


Figure 2. 12 Percent Dye Stained Matrix for Clarksburg L2P9 (top) and L2P10 (bottom), the dark lines represent means, light lines represent confidence intervals, and dashed lines represent horizon boundaries

Table 2. 1 Berks morphological data and horizon analysis

Location / Plot	Depth cm	Horizon	Field texture	% Rock fragments	Structure	% Stained	P value
L1 P4	9	Ap	Channery Silt Loam	20	GR	70.6	0.000
L1 P4	25	Bw1	Very Channery Silty Clay Loam	55	SBK	55.8	0.000
L1 P4	40	Bw2	Extremely Channery Silty Clay	80	SBK	24.8	
L1 P4	60	C	Extremely Channery Silty Clay loam	85	MA		
L1 P4	>60	R					
L1 P5	10	Ap	Channery Silt Loam	20	GR	68.5	0.065
L1 P5	18	BA	Very Channery Silty Clay Loam	50	SBK	57.3	0.001
L1 P5	40	Bw	Extremely Channery Silty Clay	70	SBK	36.6	0.003
L1 P5	64	C1	Extremely Channery Silty Clay	85	MA	12.1	
L1 P5	>64	C2					
L2 P11	15	Ap	Channery Silt Loam	20	PL - GR	42.5	0.000
L2 P11	33	Bw	Very Channery Silty Clay Loam	45	SBK	7.6	0.284
L2 P11	51	C	Extremely Channery Silt Loam	88	SBK	10.5	
L2 P11	>51	R					
L2 P12	10	Ap	Channery Silt Loam	30	PL - GR	55.2	0.000
L2 P12	28	Bw	Very Channery Silty Clay Loam	37	SBK	8.1	0.922
L2 P12	38	C	Extremely Channery Silt Loam	88	SBK	8.6	0.729
L2 P12	>38	R				7.7	

Structure GR-Granular, SBK-Subangular Blocky, Pl-Platy, PR-Prismatic, MA-Massive, COL-Columnar

Table 2. 2 Buchanan morphological data and horizon analysis

Location / Plot	Depth cm	Horizon	Field texture	% Rock fragments	Structure	% Stained	P value
L1 P1	5	A	Sandy Loam		GR	76.7	0.009
L1 P1	24	Ap	Sandy Loam		SBK	61.7	0.486
L1 P1	34	Bt1	Sandy Loam		SBK	64.2	0.000
L1 P1	58	Bt2	Sandy Clay Loam		SBK	26.2	0.002
L1 P1	86	Bx1	Sandy Loam	1	PR - SBK	3.6	0.006
L1 P1	>86	Bx2	Sandy Clay Loam	1	PR - SBK	1.4	
L1 P2	8	A	Sandy Loam		GR	69.4	0.363
L1 P2	28	Ap	Sandy Loam		SBK	63.6	0.000
L1 P2	58	BE	Loamy Sand		SBK	13.8	0.004
L1 P2	89	Bx1	Sandy Loam		PR - SBK	2.2	0.050
L1 P2	>89	Bx2	Sandy Loam		PR - SBK	0.8	
L2 P13	8	Ap1	Sandy Loam	1	PL	82.5	0.008
L2 P13	24	Ap2	Sandy Loam		PR - PL	64.8	0.000
L2 P13	51	Bt	Sandy Loam		PR - SBK	29.7	0.002
L2 P13	76	Btx1	Sandy Clay Loam		PR - SBK	16.9	0.058
L2 P13	>76	Btx2	Sandy Loam		PR - SBK	7.2	
L2 P14	10	Ap1	Sandy Loam		PL - GR	79	0.008
L2 P14	23	Ap2	Sandy Loam		PR - SBK	58.9	0.000
L2 P14	36	Bt	Sandy Loam		PR - SBK	37.4	0.003
L2 P14	51	Btx1	Sandy Clay Loam		PR - SBK	15.7	0.490
L2 P14	94	Btx2	Sandy Loam		PR - SBK	13	
L2 P14	>94	BCt	Sandy Loam		PR		

Structure GR-Granular, SBK-Subangular Blocky, Pl-Platy, PR-Prismatic, MA-Massive, COL-Columnar

Table 2. 3 Clarksburg morphological data and horizon analysis

Location / Plot	Depth cm	Horizon	Field texture	% Rock fragments	Structure	% Stained	P value
L1 P6	5	Ap1	Silt Loam		GR	90.5	0.011
L1 P6	13	Ap2	Silt Loam		PL - SBK	81.3	0.000
L1 P6	25	Bt1	Clay Loam		MA - PL	36.7	0.202
L1 P6	43	Bt2	Clay Loam		PR - SBK	29	0.000
L1 P6	69	2Bt3	Channery Clay	27	SBK - PL	14.7	0.000
L1 P6	>69	3Bt4	Clay		SBK	4.7	
L1 P8	8	Ap1	Silt Loam	2	GR	93.1	0.000
L1 P8	15	Ap2	Silt Loam	10	PL - SBK	79.6	0.000
L1 P8	36	Bt1	Clay Loam	5	PR - SBK	32.7	0.000
L1 P8	61	Bt2	Clay Loam	5	SBK	5.7	0.035
L1 P8	>61	Bt3	Clay	5	SBK	2.6	
L2 P9	23	A	Silt Loam	2	GR	67.2	0.000
L2 P9	53	Bt1	Silty Clay Loam	5,3	SBK	21.9	0.000
L2 P9	79	Bt2	Clay	5,2	SBK	10.5	0.065
L2 P9	>79	Bt3	Clay	2	SBK	5.5	
L2 P10	23	A	Silt Loam	1	GR	74.9	0.000
L2 P10	53	Bt1	Clay Loam	2	SBK	47.9	0.000
L2 P10	94	Bt2	Clay	1,1	SBK	14.1	
L2 P10	>94	Bt3	Clay	5	SBK - PL - SBK		

Structure GR-Granular, SBK-Subangular Blocky, Pl-Platy, PR-Prismatic, MA-Massive, COL-Columnar

CHAPTER 3: PHOSPHORUS TRANSLOCATION IN PASTURES ON BENCHMARK SOILS IN WEST VIRGINIA

Abstract

Safe, long-term application of phosphorus (P) from animal manure to satisfy crop nitrogen (N) demands is dependent on a soil's ability to sorb any excess P. It is assumed the soil sorbs any excess P and as sorption capacity is filled, unsorbed phosphorus will move down parallel to the surface and be sorbed by the less saturated soil below. Preferential flow can bypass significant portions of the soil matrix invalidating this assumption. Consequently, the occurrence of preferential flow could lead to a deeper distribution of P in the soil profile. Three benchmark soil series common to pastures in West Virginia were selected for study. FD&C Blue # 1 dye was applied in a ponding fashion to identify active macropores. The applications sites were excavated and composite soil samples were collected from the stained and unstained matrix within each horizon. The soil samples were analyzed for phosphorus with Mehlich-1 extractions. Overall the P levels in the stained matrix samples were higher than the unstained samples at a statistically significant level. Generally the P levels declined with depth, in both the stained and unstained matrix samples. The implication of these findings on the long term management of P outlines a need for additional study to insure protection of the environment while maintaining agronomic productivity.

Introduction

With preferential flow, percolating water bypasses portions of the porous matrix (Hendrickx and Flury, 2001). Pathways for preferential flow may include inter-aggregate pore spaces, earthworm burrows, gopher holes, shrink-swell cracks, decayed root channels, and other structures or conditions which generate a pathway more conducive to water movement (Nielsen et al., 1986). Many of these pathways maintain their integrity over time thus restricting saturation of the remaining soil matrix (Dekker et al., 2001). Preferential flow properties are variable within the profile and across the landscape (Strock, 2001). Furthermore, preferential flow occurs in many soil textures, structures (Wang et al., 1998), degrees of saturation (Hammermeister et al., 1982; Jardine et al., 1989; Wilson et al., 1997), depths, and textural interfaces in the soil profile (Heppell et al., 2000a, b).

Elevated levels of P in the soil have been attributed to applications of animal manures as a fertilizer to satisfy N requirements. Historically, animal manures have been over-applied on some farms, particularly near confined animal feeding operations. Regionally high densities of food animal agriculture and N based manure applications could lead to elevated P saturation and an increased risk of water quality impairment (Beck et al., 2004). In eastern West Virginia, Grant, Hardy, and Pendleton Counties have robust food animal agriculture production and producers in these counties generate quantities of animal manures commensurate to their production levels. A better understanding of preferential flow and potential nutrient translocation within the soils in this region could prove reduce P loss, and protecting the aquatic environment.

In agricultural soils, preferential flow can be quite common (Petersen et al., 1997). Preferential flow has been shown to promote translocation of soil particles within the soil profile (Oygarden et al., 1997). No-till management practices lead to soils with more macropore pathways suitable for the preferential flow of water (Petersen et al., 1997). The increased macropore pathways in no-till soils may be a result of the accumulation of water repellant organic matter, the establishment of stable surface connecting macropores, or both (Hallett et al., 2001). This combination likely increases the movement of water deeper into the soil profile. According to Akhtar et al. (2003), soil structure is a good indicator of the potential for preferential flow, and Kim et al. (2004) found correlations between the texture and the structure of soil horizons and the staining patterns used to identify preferential flow.

Dye tracing experiments are commonly used to identify patterns of water movement within soil profiles (Morris and Mooney, 2004). Dye tracer experiments have been used to generate qualitative information about water movement in soil profiles (German-Heins and Flury, 2000; Weiler and Nae, 2003). The dye patterns from tracer experiments are often used to differentiate flow types as a part of an overall sampling strategy (Reichenberger et al., 2002). Most dye tracing experiments look at a scale of a few square meters.

The potential impact of preferential flow on surface applied manure has far-reaching consequences. Many models of P interactions currently used in P indexes indicate that P is not readily leached from most soils because it will be sorbed by the nearly inexhaustible sorption capacity of the subsurface soil horizons (Pepper et al., 1996). This model is dependent on a piston like movement of water and the consequent distribution of mobile P. Most models used to describe or simulate water movement through unsaturated soil, assume uniform, stable infiltration, which is uncommon in most field soils (Dekker et al., 2001). Preferential flow is one such exception to this assumption, and this may be of practical significance and should be examined.

The National Agricultural Statistics Service reported in 2002 that for three counties in eastern West Virginia (Grant, Hardy, and Pendleton) there was 85% of the state's broilers and other meat-type chicken sales, or approximately 77,419,965 chickens, and about 15% of the state's cattle sales, or approximately 35,439 head (NASS, 2002). Much of the animal wastes in these three counties are applied as fertilizers on row crops and pastures (Basden et al., 1994). Row crop production has at least some capacity to remove soil P via the harvest, but pastures approximate a closed system where the only P export in an agronomic sense is in animal tissues moved from the farm. Of the total farm acres in Grant, Hardy, and Pendleton Counties, only 26% are cropland (NASS, 2002). Assuming that a majority of the animal manures is applied to hay and grass pastures, P retention could become very problematic. At the county level, if any counties in West Virginia are likely have a P retention problem it is most likely one of these counties.

The objective of this research is to measure the soil test P levels in preferential flow pathways and the surrounding soil matrix, and determine if extractable P was greater near these flow paths, which may indicate P is moving within the preferential flow pathways.

Hypothesis

In pastures and grasslands of eastern West Virginia fertilized with animal manures, preferential flow has facilitated the translocation of P through the soil profile bypassing portions of the soil matrix, leading to the elevated P levels in the soil materials immediately surrounding the preferential pathways.

Materials and Methods

Experimental Design

The experimental design was a three stage nested design (Fig. 3.1): location nested in series, investigative plots nested in location, and target applications nested in investigative plots (Dowdy et al., 2004). Field experiments were conducted at two locations per selected benchmark soil series. At each location, two investigative plots were identified for study. In each investigative plot, two target applications of dye were made. This produced 24 target applications, with eight for each series. The target applications were arranged so they were approximately five to six feet apart.

Series and Location Selection

Given the lack of published data on preferential flow in naturally drained pasture soils of West Virginia, the extent, taxonomic significance, and local importance of benchmark soils make them ideal for comparisons to other series.

As such, benchmark series were selected from the most common series under grass and hay management schemes in Grant, Hardy, and Pendleton Counties, the three West Virginia counties that produce 87% of the broiler sales and 15% of the cattle sales (NASS, 2002). The selection was made by combining published soils series map data and published land cover data to rank the abundance of series under the land uses of interest. The presence of important or unique soil morphological features (e.g., fragipans, shallow bedrock, high rock fragment content, and differences in mineralogy) was also considered so there would be diversity and contrast among the benchmark series selected.

These series were selected based on availability of cooperative landowners. Specific locations for each series were chosen on farms which utilized primarily animal manure for fertilizers over the previous decade, and were currently used as hay or grass pasture fields. The specific plots within the locations were chosen based on topography (areas < 10% slope), with potential locations identified from published soil survey maps. These locations were excavated with an auger and compared to the official series description to determine if these locations was likely the series of interest.

Three benchmark soils series that are of large extent in eastern West Virginia were selected for this study: Berks (Loamy-skeletal, mixed, active, mesic Dystrudepts), Buchanan (Fine-loamy, mixed, semiactive, mesic Aquic Fragiudults), and Clarksburg (Fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs) . Berks occurs to the greatest extent under grassland and hay pasture land uses in Grant, Hardy, and Pendleton counties and is characterized by high rock fragments contents and moderately deep depths to bedrock. Buchanan and Clarksburg have fragipans but Clarksburg soils have relatively higher base saturations values associated with parent materials with more limestone influence. The Buchanan and Clarksburg series are less rocky than Berks, and are among the top 25 series in terms of extent under grassland and hay pasture land uses in Grant, Hardy, and Pendleton counties. The differences in soil morphological and chemical properties may influence water movement.

Dye Application

The positions of the investigative plots within a location were selected from locations with <10% slope, which facilitated a more even infiltration of the dye solution. Prior to dye application, the vegetation in the investigative plots was trimmed to an approximate height of 5 cm, and trimmed plant material was removed from the plot area.

Preferential flow pathways were identified in a fashion similar to the methods described by Flury et al. (1994). Flury et al. (1994) flood irrigated with a solution of Blue 1 at a concentration of 4 kg/m^3, using a total solution volume of 40 L/m^2. The dye was applied from a large sprinkling nozzle in less than one minute to a 1 m^2 infiltrometer ring driven into the soil to a depth of 20 cm. Ponding infiltration initiates the deeper, macropore flow component of preferential flow better than a slower simulated rainfall type application (Flury et al., 1994).

For this research, ponding of the dye on the soil surface on each one square meter target application was facilitated using reinforced steel containment apparatus of my design (Fig. 3.2). The containment apparatus were 1.3 m long, 1.3 m wide, and 0.3 m tall sheet metal frames that permitted controlled application the dye to the soil surface over an area larger than one square meter, thus limiting border affects. Along the bottom of each apparatus, the soil surface was opened with hand tools to form a slice that paralleled the bottom of the apparatus. Each apparatus was then pounded into the slice in the soil surface to an approximate depth of approximately 10 cm. The interface between the apparatus and the soil surface was sealed with a simple sodium bentenite mortar to limit leakage.

The dye used in this research was FD&C Brilliant Blue #1 powder (Blue 1). Blue 1 is a dark blue-purple powder and is used as a food additive primarily in beverages, bakery goods, dessert powders, candy, and confections. Blue 1 in solution is a brilliant greenish blue color. It is resistance to light and to heat. The chemical name Blue 1 is ethyl (4-{para [ethyl (meta-sulfobenzyl) amino]-a-(ortho-sulfophenyl) benzylidene}-2, 5- cyclohexadien-l-ylidene) (meta-sulfobenzyl) ammonium hydroxide inner salt, disodium salt (CCOHS, 1978). Dyes as tracers are commonly used in scientific investigation of subsurface flow, and Blue 1 is the most commonly used dye (Flury and Wai, 2003).

Each target application was flood irrigated with a solution of Blue 1 at a concentration of 4 kg/m^3. A total solution volume equal to 40 liters of dye solution per square meter of the containment apparatus area was applied from a storage container in approximately two minutes to facilitate near instantaneous ponding (Flury et al., 1994). Trimmed vegetative cover was left on the target applications to reduce the impact of the rapid application of the dye solution. The dye application was allowed to fully infiltrate the soil surface.

This method works well on flat surfaces. However, at greater slope gradients there is uneven distributing the dye. At steeper gradients the dye is redistributed in the containment apparatus becoming deeper at the lower end of the containment apparatus and shallower at the upper end. As a result, the depth of dye can be in excess of the targeted depth of 4 cm at the lower side of the containment apparatus and less than 4 cm at the upper side. Consequently, more dye was applied to the lower segments of the application area and less to others. Images were collected from multiple pit faces to minimize this effect. One application was sampled four to five times in the up slope direction. The other application was sampled four to five times in the down slope direction.

Excavation and Site Preparation

Two to three days were allowed for the stained soil to partially dry after the application. Attempts to excavate on the day after application produced smearing of the dyed soil across each pit face. After the two to three day waiting period, a pit was excavated in each plot between the paired target applications. After initial excavation of the area between the paired target application areas, a full field description of the soil was performed using standard field methods (Schoeneberger et al., 2002). The % rock fragments, field textures, structures, colors, boundaries, motels, and redoximorphic features were described for each plot. In each target application, the central square was processed such that multiple vertically exposed profiles within the central square meter of the target application were available for sampling (Flury et al., 1994). One of these vertically exposed soil profiles in the central square meter of a target application constitutes a pit face. Each pit face was prepared by trimming away soil to even up the profile, and remove loose materials, smears, smudges, or equipment marks prior to sample collection. This was necessary to insure areas treated as stained were in fact stained by dye and water movement and not by transfer during the excavation process.

Soil Sampling

Samples of both stained and unstained soil were collected from each genetic horizon as identified by the profile descriptions (Sinaj et al., 2002). As the percent stained matrix approaches extremely high and extremely low levels the samples become more biased. This is partially mediated by composite sampling. For each target application, both stained and unstained samples from each horizon were composited across the pit face and among all pit faces (Fig. 3.3). Consequently, each target application produced a composite stained and an composite unstained sample for each genetic horizon. Additional composite samples were collected from each horizon without differentiating between stained and unstained soil. The purpose of these samples was to facilitate measurement of pH, CEC, and texture with out consideration of stained status. After returning the samples to the laboratory, large plant residues such as roots were removed from the soil samples. The samples were air-dried and sieved to <2mm (Sinaj et al., 2002).

There was difficulty in collection of discretely stained or unstained samples in some horizons. Near the surface, unstained soil was limited. In some instances, in surface horizons there was no unstained material in some pit faces. Near the bottom of the pit, the stained matrix was limited. In some instances, in lower soil horizons, there was no stained material in some pit faces. Every effort was made to minimize the inclusion of unstained soil materials in stained samples and stained materials in unstained samples.

Extraction Based Soil Testing

To assess the available nutrient status of soils, specific extractants are used too rapidly estimate the nutrients present in the soil (Wolf and Beegle, 1995). Typically, specific recommendations for any needed fertilization is based on the amount of a given nutrient present in an extractant after it has been exposed to a soil sample (Wolf and Beegle, 1995). The West Virginia University Soil Testing Laboratory uses the Mehlich-1 (Nelson et al., 1953) extractant, which is a strong acid extractant. Such soil test P (STP) results are used as an approximation of the nutrients bioavailability in the soil. Maguire and Sims (2002) demonstrated that STP results from Mehlich-1 extractions can be used to estimate P leaching potential, as Mehlich-1 data are nearly as accurate as environmental P test results. Beck et al. (2004) found that while not developed for this purpose, Mehlich-1 soil test phosphorus (STP) data were an adequate indicator of environmental risk.

Mehlich-1 was used to measure STP and, by inference, the P leachability. The method was developed to predict plant available P, but has show to be a good indicator for the degree of P saturation in a soil which can indicate the potential for leachability (Beck et al., 2004) In brief, a Mehlich-1 extraction involves introducing 25mL of 0.025 N H_2SO_4 + 0.05 N HCl with 5 cm^3 of soil in a 150 mL, and 1 cm^3 of activated carbon in an extraction flask and shaking it for five minutes on a reciprocating shaker set at a minimum of 180 oscillations per minute (Nelson et al., 1953). Next, the extractant is filtered through a medium-porosity filter paper (Whatman No. 2 or equivalent) and analyzed for P content (Nelson et al., 1953). Many soil test labs have developed their own specific version of the Mehlich procedure. Typically, they involve specific ratios of soil to extractants and sample volumes or weights. The specific extraction procedures used in this research were the variation used by the West Virginia soil-testing laboratory. The P levels in the Mehlich-1 extractants were analyzed with a Perkin Elmer P4000 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

Statistical Analysis

For statistical analysis purposes, the data were analyzed for normality and outliers. The data were found to include several outliers, and the data did not fit an approximation of the standard normal distribution. This was corrected with a log transformation of the data. After transformation, the Quantile Quantile plot for the data showed a more linear approximation which indicates the presence of a more standard normal distribution of data, and the extreme outliers were eliminated. The log-transformed data were examined by analysis of variance (ANOVA) in the GLM procedure in SAS (SAS Institute. 1994).

Results and Discussion

STP levels ranged from a low of 0.25 mg/kg in the Clarksburg series (L2 P10 A2) stained Bt2 horizon sample (53 to 94 cm) to a high of 1480.50 mg/kg in the Berks series (L1 P4 A1) unstained Ap sample (0 and 9 cm). When the stained and unstained STP levels were combined across all horizons at the series level, the means ranged from a low of 16.93 mg/kg in the Buchanan series to a high of 393.89 mg/kg in the Berks series (Table 3.1). The high and low values corresponded with the expected past applications of animal manure. The Buchanan locations were on West Virginia University Experiment Station farms, where limited manure was generated from cattle and poultry and more informed management decisions should be expected. Conversely, the Clarksburg locations were on poultry farms. One of these locations has ceased active fertilization with poultry manure due to elevated STP levels observed in soil samples taken during their nutrient management process. One Berks location is on a poultry farm with limited pasture resources and approximately 30 years of production. The remaining Berks location is in an area where neighboring poultry farms are so abundant it is likely the cost of fertilization with poultry manure would have been low. STP levels for each sample can be examined in Appendix 2.

When the appropriate error terms were used in the ANOVA, the log-transformed data showed no significant differences at the $p < 0.05$ level in the STP data at the series level. The correct error term for this analysis of the series is the mean square for the location. The log-transformed data was significantly different at the location level ($p=0.0178$) after the correct error term was used in calculation of the F value. The Correct error term for location was the mean square for plot. The mean square for error was the correct term used in calculating the F values for the remaining analysis. The data was not significantly different at the plot level ($p=0.0867$), or application level ($p=0.3966$). The plot level of significance ($p=0.0867$) suggests that sufficient plot level variance exists to be considered for closer consideration in future research of similar design. The analysis of variance shows a significant difference between the STP levels associated with the stained and unstained samples ($p=0.0007$) and STP levels related to horizons ($p < 0.0001$) (Table 3.2). The full statistical analysis can be examined in Appendix 3.

Location effect is likely to be more closely related to management. While detailed historic information on nutrient applications is not known for the study sites, it is certain that not all locations have received the same fertilizer amounts over the years. This pretext matches the data analysis. Plot differences may be mostly a result of variability within fields. Such variability at the field scale is expected, however, it should be less than the variability between locations. Similarly, because of the nested design, differences among the applications are expected less than the differences between plots.

The significant difference between the STP levels in the stained and unstained sample indicates the possibility of STP levels being higher in the stained samples (140.02 mg/kg) than in the unstained samples (118.07 mg/kg). Stained STP values at depth in excess of their paired unstained STP values were common, but not always the case. In some instances, the unstained samples had higher STP levels. Macropores which previously translocated P and / or contain decaying organic matter, but are no longer connected to the surface are possible causes of this condition. Within the stained and unstained samples, the higher STP levels were found near the surface and the lower STP levels in the deeper horizons. About 76 percent of the time, the stained samples had higher STP levels than unstained samples (Table 3.1). When the STP levels in unstained samples were higher than the stained sample, 36% of the occurrences were in surface horizons, and over 40% of the remaining occurrences were near the surface.

Unexpected STP levels in both the stained and unstained samples could be explained by many processes. A localized resistance to dye penetration at the surface unrelated to the general properties associated with that soil series could alter dye penetration, phosphorus translocation, and root penetration. Likewise, if the dye followed plant roots, it is possible the plants have used portion of P thus lowering the STP levels in the stained samples. All research plots less Buchanan L1 P1 and L1P2 are used frequently to pasture cattle. The compaction of the top 10 to 15 cm from cattle grazing on moist soils could create some portion of the surface where porosity was reduced. When these factors are considered along with the timing of recent and historic manure applications, instances of higher relative P levels an unstained sample are reasonable occurrences. The occurrence of unstained STP values exceeding the stained values was noted in all series.

Conclusions

P interactions in the soil do not appear to prevent the downward movement of P within these soil profiles. However, the P interactions in the soils do appear to limit the STP levels with depth. Generally, the higher STP levels are found closer to the soil surface and STP levels decline as you sample deeper horizons. Overall, the STP levels in the stained sampling areas (presumed preferential flow paths) are higher than the unstained soil matrix. This is consistent with the hypothesis.

If P moves in an uneven manner in the soil there should be distinct regions with elevated P levels relative to the P level associated with that depth or horizon. It is likely these regions would be found in the soil matrix closest to the pathways that are believed to be responsible for an uneven distribution of P. Thus, samples collected from portions of the soil profile in regions identified by the dye application used to identify preferential flow would be expected to have higher P levels if they were transporting P through the soil profile. The results suggest that P has moved through the soil profile in an uneven manner, bypassing portions of the soil matrix.

There were no significant differences in STP levels among the soil series examined in this study. Locations were significantly different in terms of STP results. Localized management should, or at least potentially could, lead to just such results. The similarity within plots and applications was expected within fields because of their proximity top each other. The overall significant differences between the stained and unstained samples indicates uneven P movement through the soil profile.

The potential for environmental problems could increase if there is documented irregular movement of P in the soil profile. How the P moves, its source, and its availability to plants could mediate some aspects of this concern. The possibility of P moving toward the ground or surface waters faster then expected makes the consideration of such possibilities in management decisions important

Modification of management decisions cannot be based solely on these data. The sites selected were diverse, and the P saturation status was not considered when selecting sites. There are also some limitations in terms of scale, and landscape position. However, these data are consistent with the current literature on preferential movement of P.

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Figures and Tables

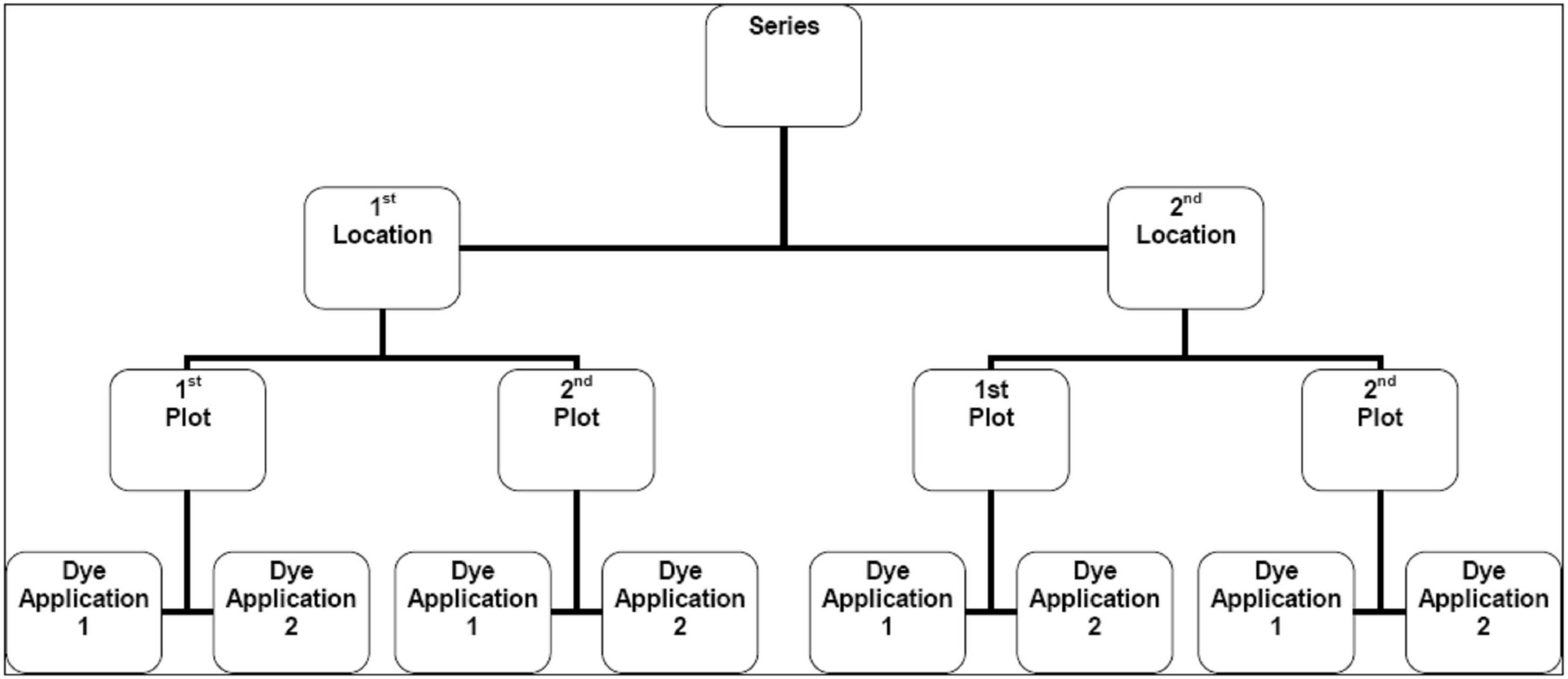

Figure 3. 1 Three stage nested design

Figure 3. 2 Steel reinforced 1.3 meter by 1.3 meter dye containment apparatus used to facilitate dye ponding and infiltration

Figure 3. 3 Stained and unstained samples collected for STP analysis by Mehlich-1 extractions

Table 3. 1 Summary statistics soil test phosphorus data

	Soil Series			Matrix	
	Berks	Buchanan	Clarksburg	Stained	Unstained
	n				
Horizon Samples	58	88	64	105	105
	mg/kg				
Mean STP	393.89	16.93	46.45	142.02	118.07
Median STP	95.40	11.58	4.39	18.19	12.03
Minimum	3.66	0.595	0.25	0.25	0.25
Maximum	1480.5	76.6	340.1	1366	1480.5
Standard Error	67.22	1.73	11.94	31.48	30.70

Table 3. 2 Soil test phosphorus analysis of variance

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Series	2	294.09	147.04	1.08	0.4802
Location	2	271.69	135.84	55.13	0.0178
Plot	2	4.92	2.46	2.48	0.0867
Application	1	0.71	0.71	0.72	0.3966
Treatment	1	1.92	11.92	11.98	0.0007
Depth	1	39.56	239.56	240.68	<.0001

CHAPTER 4: CONCLUSIONS

The impact of preferential flow on manure management in the poultry producing counties of eastern West Virginia may require land manager to reconsider of how land applications of animal manures and nutrient are managed. This research has shown there is a potential for preferential flow in some of the common pasture soils found in these animal agriculture regions of the state (Chapter 2). P translocation and deposition within the soil profile may be significantly different where active movement of water is occurring (Chapter 3). Given these conditions, it is reasonable to assume that P could move deeper into the soil profile and possibly into surface waters or groundwater via preferential flow. The difficulty is in determining if the difference in P levels at depth is of practical significance to the protection of the environment.

This research has demonstrated the occurrence of preferential flow when ponded infiltration occurs in hay and grass pastures in three benchmark soil series. This research identifies likely qualitative relationships between changes in soil profile morphology, water movement, and preferential flow. Changes in dye staining patterns always coincided with some change in structure, texture, or percent rack fragments. When flow is confined or ponded by morphological features translocation could be affected. This research has shown STP levels through the soil profiles in a pattern that is consistent with the preferential pathways of water. The data collected indicates P levels are reduced as a function of depth, but there are additional significant differences in P levels in relation to proximity to preferential flow paths. It is unclear how this ultimately affects P sorption capacity of farm fields, but at a minimum, some part of most fields will have less capacity to sorb P because of preferential flow limiting contact between P and the soil matrix. The results of this research in hay and grass pastures with primarily animal manure fertilization agree with the current literature in regards to the presence of preferential flow (Bouma et al., 1977; Flury et al., 1994; Peterson et al., 1997; Mohanty et al., 1998; Stamm et al., 1998), and the ability of preferential flow to transport P (Sinaj et al., 2002; Grant et al., 1996; Hodgkinson et al., 2002; Campbell et al., 1995).

The examination of the theoretical underpinnings of management decisions should always be practiced. Such examination is fundamental to making good decisions. Experiments designed to answer specific questions that can help us decide if there is a practical significance that needs to be addressed should be pursued. If preferential flow is demonstrated to be a normal occurrence, it would become necessary to examine the fate of P within the preferentially moving fluids. Future determinations about P entering groundwater or surface waters via preferential flow will be needed. It is likely we will need new estimates of the volume of soil available to contain P leached within the soil profile. Ultimately, this could reduce the long-term ability of some fields to utilize N-based manure applications, which often lead to the over application of P. Additional study is needed to determine how and when we should proceed with adding preferential flow in the management decision-making process.

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APPENDICES

Appendix 1 profile descriptions

Berks L1-P4

(Colors are for moist soil unless otherwise noted.)

Slope	8%
Land use	grass hay
State	West Virginia
County	Pendleton
Date	10/26/2007

Ap--0 to 9 cm; brown (10YR 4/3) channery silt loam; weak fine granular structure; very friable; 20 percent very angular shale channers; pH 6.51(water) 6.12($CaCl_2$); clear boundary.

Bw1--9 to 25 cm; strong brown (7.5YR 4/6) very channery silty clay loam; weak fine subangular blocky; friable; 55 percent very angular shale channers; pH 6.36(water) 5.97($CaCl_2$); gradual boundary.

Bw2--25 to 40 cm; strong brown (7.5YR 5/8) extremely channery silty clay; weak fine subangular blocky; friable; 80 percent very angular shale channers; few medium distinct gray (2.5Y 5/1) iron depletions; pH 5.68(water) 5.13($CaCl_2$); gradual boundary.

C--40 to 60 cm; gray (2.5Y 6/1) extremely channery silt clay loam; massive; 85 percent very angular shale channers; common medium distinct strong brown (7.5 YR 5/6) iron concentrations; pH 4.76(water) 4.21($CaCl_2$); clear boundary.

R--60 + cm; fractured shale bedrock

Berks L1-P5

(Colors are for moist soil unless otherwise noted.)

Slope	10%
Land use	grass hay
State	West Virginia
County	Pendleton
Date	10/26/2007

Ap--0 to 10 cm; dark yellowish brown (10YR 3/4) channery silt loam; weak medium granular structure; friable; 20 percent angular shale channers; pH 6.75(water) 6.32($CaCl_2$); clear smooth boundary.

BA--10 to 18 cm; dark yellowish brown (10YR 3/4) very channery silty clay loam; weak fine subangular blocky; friable; 50 percent angular shale channers; pH 7.06(water) 6.62($CaCl_2$); clear smooth boundary.

Bw--18 to 40 cm; strong brown (7.5YR 4/6) extremely channery silty clay; weak fine subangular blocky; friable; 70 percent very angular shale channers; pH 6.79(water) 6.26($CaCl_2$); gradual wavy boundary.

C1--40 to 64 cm; strong brown (7.5YR 5/6) extremely channery silty clay; massive; friable; 85 percent very angular shale channers; diffuse wavy boundary.

C2--64 + cm; fractured shale.

Berks L2-P11

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass hay
State	West Virginia
County	Pendleton
Date	7/19/2007

Ap--0 to 15 cm; dark brown (10YR 3/3) channery silt loam; weak very thin platy parting to weak very fine granular structure; very friable; 20 percent very angular shale channers; pH 5.90(water) 5.42($CaCl_2$); very abrupt smooth boundary.

Bw--15 to 33 cm; strong brown (7.5YR 5/6) very channery silty clay loam; weak medium subangular blocky; friable; 45 percent very angular shale channers; pH 6.10(water) 5.57($CaCl_2$); clear wavy boundary.

C--33 to 51 cm; strong brown (7.5YR 5/6) extremely channery silt loam; weak very fine to fine subangular blocky; very friable; 88 percent very angular shale channers; pH 5.82(water) 5.22($CaCl_2$); clear wavy boundary.

R--51+ cm; highly fractured lithic materials, but not a lithic contact.

Berks L2-P12

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass hay
State	West Virginia
County	Pendleton
Date	7/19/2007

Ap--0 to 10 cm; dark brown (10YR 3/3) channery silt loam; weak thin platy parting to weak fine granular structure; very friable; 30 percent very angular shale channers; pH 6.39(water) 6.01($CaCl_2$); very abrupt smooth boundary.

Bw--10 to 28 cm; strong brown (7.5YR 5/6) very channery silty clay loam; weak medium to coarse subangular blocky parting to weak fine subangular blocky; friable; 37 percent very angular shale channers; pH 6.44(water) 5.92($CaCl_2$); clear wavy boundary.

C--28 to 38 cm; strong brown (7.5YR 5/6) extremely channery silt loam; weak fine subangular blocky; very friable; 88 percent very angular shale channers; pH 5.82(water) 5.28($CaCl_2$); abrupt wavy boundary.

R--38+ cm; highly fractured lithic materials fractured every 5cm latterly and every 2.5cm in horizontal plane.

Buchanan L1-P1

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass hay
State	West Virginia
County	Hardy
Date	8/3/2006

A--0 to 5 cm; dark grayish brown (2.5Y 4/2); sandy loam; moderate medium granular structure; friable; pH 5.45(water) 4.97($CaCl_2$); clear boundary.

Ap--5 to 24 cm; dark grayish brown (2.5Y 4/2); sandy loam; weak medium subangular blocky structure; very friable; pH 5.64(water) 5.11($CaCl_2$); abrupt boundary.

BE--24 to 34 cm; light olive brown (2.5Y 5/4); sandy loam; weak medium subangular blocky structure; friable; pH 5.98(water) 5.42($CaCl_2$); gradual boundary.

Bt--34 to 58 cm; yellowish brown (10YR 5/6); sandy clay loam; moderate medium subangular blocky structure; friable; pH 6.10(water) 5.53($CaCl_2$); clear boundary.

Bx1--58 to 86 cm; dark yellowish brown (10YR 4/6); sandy loam; weak coarse prismatic parting to moderate medium subangular blocky structure; firm; 1 percent subangular sandstone gravels; common medium distinct light gray (10YR 7/2) iron depletions; pH 5.78(water) 5.18($CaCl_2$); gradual boundary.

Bx2--86+ cm; brownish yellow (10YR 6/6); sandy clay loam; weak coarse prismatic parting to moderate medium subangular blocky structure; friable; 1 percent subangular sandstone gravels; common medium distinct light gray (10YR 7/2) iron depletions; pH 5.24(water) 4.59($CaCl_2$).

Buchanan L1-P2

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass hay
State	West Virginia
County	Hardy
Date	8/3/2006

A--0 to 8 cm; very dark grayish brown (10YR 3/2) sandy loam; weak medium granular structure; very friable; pH 5.38(water) 4.92($CaCl_2$); clear boundary.

Ap--8 to 28 cm; dark yellowish brown (10YR 4/4) sandy loam; weak medium subangular blocky structure; very friable; pH 5.57(water) 4.93($CaCl_2$); abrupt boundary.

BE--28 to 34 cm; light yellowish brown (10YR 6/4) loamy sand; weak medium subangular blocky structure; very friable; pH 6.03(water) 5.48($CaCl_2$); clear boundary.

Bx1--34 to 89 cm; light olive brown (2.5Y 5/4) sandy loam; moderate coarse prismatic parting to moderate medium subangular blocky structure; firm; common medium distinct light gray (10YR 7/2) iron depletions; pH 6.41(water) 5.81($CaCl_2$); gradual boundary.

Bx2--89+ cm; yellowish brown (10YR 5/6) sandy loam; moderate coarse prismatic parting to moderate medium subangular blocky structure; firm; common medium distinct light gray (10YR 7/2) iron depletions, and few fine distinct strong brown (7.5YR 4/6) iron concentration; pH 6.33(water) 5.80($CaCl_2$); gradual boundary.

Buchanan L2-P13

(Colors are for moist soil unless otherwise noted.)

Slope	6%
Land use	grass pasture
State	West Virginia
County	Hardy
Date	8/1/2007

Ap1--0 to 8 cm; very dark grayish brown (10YR 3/2) sandy loam; weak thin to thick platy structure; friable; few stripped sand grains light gray (10YR 7/1); 1 percent very angular sandstone gravels; pH 6.42(water) 5.88($CaCl_2$); abrupt smooth boundary.

Ap2--8 to 24 cm; brown (10YR 4/3) sandy loam; moderate medium prismatic parting to weak very thick platy structure; friable; few stripped sand grains very dark grayish brown (10YR 3/2), common coarse iron depletions grayish brown (2.5Y 5/2) on ped faces, few faint iron accumulations dark yellowish brown (10YR 4/6) in pores; pH 6.42(water) 5.86($CaCl_2$); very abrupt smooth boundary.

Bt--24 to 51 cm; very pale brown (10YR 7/4) sandy loam; weak medium prismatic parting to weak coarse subangular blocky structure; friable; common medium distinct dark yellowish brown (10YR 4/6) clay films; pH 6.61(water) 6.06($CaCl_2$); clear wavy boundary.

Btx1--51 to 76 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak very coarse prismatic parting to moderate coarse subangular blocky structure; very firm; many faint strong brown (7.5YR 4/6) clay films, few prominent pale yellow (2.5Y 7/4) stripped sands; pH 6.14(water) 5.68($CaCl_2$); clear wavy boundary.

Btx2--76+ cm; dark yellowish brown (10YR 4/4) sandy loam; weak very coarse prismatic parting to weak medium subangular blocky structure; very firm; common medium coarse yellowish red (5YR 5/8 and 5YR 4/6) iron accumulations, few prominent light gray (10YR 7/2) stripped sands, clear discontinuous distinct strong brown (7.5YR 4/6) clay films on faces in pores; pH 5.64(water) 5.12($CaCl_2$); clear wavy boundary.

Buchanan L2-P14

(Colors are for moist soil unless otherwise noted.)

Slope	6%
Land use	grass pasture
State	West Virginia
County	Hardy
Date	8/1/2007

Ap1--0 to 10 cm; very dark grayish brown (10YR 3/2) sandy loam; weak thin platy parting to moderate coarse granular structure; friable; common coarse dark grayish brown (10YR 4/2) iron depletions, and few fine strong brown (7.5YR 4/6) iron concentrations on pore linings; pH 6.60(water) 6.15($CaCl_2$); clear smooth boundary.

Ap2--10 to 23 cm; brown (10YR 4/3) sandy loam; weak medium prismatic parting to weak medium and coarse subangular blocky structure; friable; common coarse very dark grayish brown (10YR 3/2) iron concentrations in cracks, and few medium dark brown (7.5YR 3/3) lithochromic mottles; pH 6.38(water) 5.84($CaCl_2$); very abrupt smooth boundary.

Bt--23 to 36 cm; yellowish brown (10YR 5/4) sandy loam; weak medium prismatic parting to weak medium subangular blocky structure; very firm; common very dark grayish brown (10YR 3/2) concentrations of organic stains as castings, and few skeletans light gray (10YR 7/2); pH 6.40(water) 5.85($CaCl_2$); clear wavy boundary.

Btx1--36 to 51 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak medium prismatic parting to moderate medium and coarse subangular blocky structure; very firm; common medium distinct strong brown (7.5 YR 4/6) discontinuous clay films, common coarse skeletans light brownish gray (2.5Y 6/2), and few manganese concentrations black (10YR 2/1); pH 6.40(water) 5.88($CaCl_2$); clear wavy boundary.

Btx2--51 to 94 cm; yellowish brown (10YR 5/4) sandy loam; weak very coarse prismatic parting to weak coarse subangular blocky structure; very firm; common medium continuous iron concentrations yellowish red (5YR 4/6) on ped faces, and common coarse distinct brown (7.5YR 4/4) clay films on ped faces and pore linings; pH 5.82(water) 5.27($CaCl_2$); clear wavy boundary.

BCt-- 94+ cm; light olive brown (2.5Y 5/3) sandy loam; weak very coarse prismatic structure; firm; common medium strong brown (7.5YR 4/6) iron concentrations on ped faces, very few distinct brown (7.5YR 4/4) clay films on ped faces and pore linings, and few sand lenses light gray (10YR 7/2); pH 5.25(water) 4.66($CaCl_2$); clear wavy boundary.

Clarksburg L1-P6

(Colors are for moist soil unless otherwise noted.)

Slope	2.5%
Land use	grass hay
State	West Virginia
County	Hardy
Date	5/16/2007

Ap1--0 to 5 cm; brown (10YR 4/3) silt loam; moderate fine granular; friable; pH 4.85(water) 4.36(CaCl2); clear smooth boundary.

Ap2--5 to 13 cm; brown (10YR 4/3) silt loam; weak thick platy parting to moderate fine subangular blocky; friable; pH 5.68(water) 5.31(CaCl2); very abrupt smooth boundary.

Bt1--13 to 25 cm; reddish yellow (7.5 YR 6/6) clay loam; structureless massive parting to weak very thick platy; very firm; common coarse prominent light yellowish brown (2.5Y 6/3) iron concentrations on ped faces, and few medium faint strong brown (7.5YR 4/6) iron concentrations on ped faces; pH 5.91(water) 5.40(CaCl2); abrupt smooth boundary.

Bt2--25 to 43 cm; strong brown (7.5YR 5/6) clay loam; moderate medium prismatic parting to strong coarse subangular blocky; firm; few coarse prominent gray (2.5Y 6/1) iron depletions on ped faces, and few medium distinct yellowish brown (10YR 5/8) iron concentrations on pore linings; pH 5.26(water) 4.72(CaCl2); clear wavy boundary.

2Bt3--43 to 69 cm; yellowish brown (10YR 5/4) channery clay; weak moderate subangular blocky parting to weak thin platy; friable; 27 percent very angular shale gravels; 27 percent very angular shale channers; many coarse prominent gray (2.5Y 6/1) iron depletions on ped faces, and many coarse prominent yellowish red (5YR 5/8) iron concentrations on ped faces; pH 5.09(water) 4.47(CaCl2); gradual boundary.

3Bt4--69+ cm; yellowish brown (10YR 5/4) clay; weak very coarse subangular blocky parting to weak coarse subangular blocky; firm; many coarse prominent gray (N 6/) iron depletions on ped faces, and many medium prominent strong brown (7.5YR 5/8) iron concentrations on ped faces; pH 5.67(water) 5.25(CaCl2); gradual boundary.

Clarksburg L1-P8

(Colors are for moist soil unless otherwise noted.)

Slope	2.5%
Land use	grass hay
State	West Virginia
County	Hardy
Date	6/5/2007

Ap1--0 to 8 cm; dark brown (7.5YR 3/2) silt loam; moderate medium granular; very friable; 2 percent very angular shale gravels; pH 6.44(water) 6.05(CaCl2); clear wavy boundary.

Ap2--8 to 15 cm; light olive brown (2.5Y 5/3) silt loam; weak very thin platy parting to moderate fine subangular blocky; firm; 10 percent very angular shale gravels; pH 5.87(water) 5.36(CaCl2); clear smooth boundary.

Bt1--15 to 36 cm; strong brown (7.5YR 5/8) clay loam; weak coarse prismatic parting to strong medium, to coarse subangular blocky; firm; common coarse discontinuous dark grayish brown (10YR 4/2) organic stains along pores; 5 percent very angular shale gravels; few fine prominent light yellowish brown (2.5Y 6/3) depletions on ped faces, few fine prominent strong brown (7.5YR 4/6) iron on accumulations on faces; pH 4.93(water) 4.41(CaCl2); clear wavy boundary.

Bt2--36 to 61 cm; light yellowish brown (2.5Y 6/3) clay loam; moderate very coarse subangular blocky parting to strong medium and coarse subangular blocky; very firm; 5 percent very angular shale gravels; common medium distinct gray (2.5YR 6/1) depletions on ped faces, and common coarse prominent strong brown (7.5YR 5/8) iron accumulations on faces; pH 4.66(water) 4.24(CaCl2); clear wavy boundary.

Bt3--61+ cm; strong brown (7.5YR 5/8) clay; weak very coarse subangular blocky parting to weak medium and coarse subangular blocky; firm; 5 percent very angular shale gravels; common coarse prominent gray (2.5YR 6/1) depletions on ped faces.

Clarksburg L2-P9

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass pasture
State	West Virginia
County	Pendleton
Date	6/21/2007

A--0 to 23 cm; dark brown (10YR 3/3); silt loam; strong very coarse granular parting to strong medium granular; very friable; 2 percent very angular shale gravels; pH 6.42(water) 6.04(CaCl2); clear wavy boundary.

Bt1--23 to 53 cm; strong brown (7.5 YR 5/6) silt clay loam; moderate coarse subangular blocky parting to moderate medium subangular blocky; firm; few fine iron-manganese accumulations dark reddish brown (5YR 2.5/2) on ped faces and common discontinuous distinct clay films yellowish red (5YR 4/6) on ped faces; 5 percent very angular plinthite gravels and 3 percent very angular sandstone gravels; pH 6.81(water) 6.29(CaCl2); clear wavy boundary.

Bt2--53 to 79 cm; red (2.5YR 4/6) clay; weak very coarse subangular blocky parting to moderate coarse subangular blocky; very firm; very few distinct slickensides on ped faces; common medium prominent gray (10YR 6/1) depletions on ped faces and few fine distinct strong brown (7.5YR 5/8) accumulations on ped faces; 5 percent very angular plinthite gravels and 2 percent very angular sandstone gravels; pH 6.02(water) 5.56(CaCl2); clear wavy boundary.

Bt3--79+ cm; red (2.5YR 4/6) clay; weak very coarse subangular parting to moderate coarse subangular blocky; very firm; 2 percent very angular sandstone gravels; few common distinct strong brown (7.5YR 5/8) accumulation on ped faces; common coarse prominent gray (N 6/) depletion on ped faces and root channels; pH 5.03(water) 4.48(CaCl2); clear wavy boundary.

Clarksburg L2-P10

(Colors are for moist soil unless otherwise noted.)

Slope	5%
Land use	grass pasture
State	West Virginia
County	Pendleton
Date	6/21/2007

A--0 to 23 cm; very dark grayish brown (10YR 3/2) silt loam; moderate fine granular; friable; 1 percent very angular sandstone gravels; pH 6.80(water) 6.35(CaCl2); abrupt wavy boundary.

Bt1--23 to 53 cm; strong brown (7.5YR 5/6) clay loam; moderate coarse subangular blocky parting to moderate fine and medium subangular blocky; friable; 2 percent very angular sandstone gravels; common medium depletions on ped faces light yellowish brown (2.5 Y 6/4); common fine accumulations on ped faces yellowish brown (10YR 5/8); pH 5.96(water) 5.45(CaCl2); gradual wavy boundary.

Bt2--53 to 94 cm; dark red (2.5YR 3/6) clay; weak very coarse subangular blocky parting to moderate medium subangular blocky; very firm; very few distinct slickensides; 1 percent very angular sandstone gravels and 1 percent very angular sandstone stones; few faint depletions on ped faces gray (10YR 6/1); pH 6.24(water) 5.79(CaCl2); clear wavy boundary.

Bt3--94+ cm; yellowish red (5YR 4/6) clay; weak very coarse subangular blocky parting to moderate thin platy and moderate medium subangular blocky; firm; very few distinct slickensides;2 percent very angular sandstone gravels; common coarse depletions light yellowish brown (2.5 Y 6/4) in pores, common coarse depletions gray (10 YR 6/1) on ped faces; few medium manganese accumulations black (N 2.5/) on ped faces; pH 5.05(water) 4.46(CaCl2).

Appendix 2 Soil Test Phosphorus Data

Berks

Berks STP Data

Sample identification			Mehlic-1 extractable P	
Plot	app	Horizon depth	Stained sample	Unstained sample
		---- cm ---	-------------- mg/Kg	---------------
Berks L1 P4	1	0-9	1336.50	1480.50
Berks L1 P4	1	9-25	943.50	349.50
Berks L1 P4	1	25-40	252.30	65.80
Berks L1 P4	2	0-9	1051.00	1430.00
Berks L1 P4	2	9-25	688.00	464.55
Berks L1 P4	2	25-40	266.40	253.60
Berks L1 P4	2	40-60	6.34	295.55
Berks L1 P5	1	0-10	1366.00	1468.50
Berks L1 P5	1	10-18	1320.50	1274.00
Berks L1 P5	1	18-40	928.50	1069.00
Berks L1 P5	1	40-64	448.70	112.45
Berks L1 P5	1	>64	25.37	52.25
Berks L1 P5	2	0-10	1106.00	1238.50
Berks L1 P5	2	10-18	1126.00	422.70
Berks L1 P5	2	18-40	959.00	99.65
Berks L1 P5	2	40-64	160.50	23.63
Berks L2P11	1	0-15	96.55	21.63
Berks L2P11	1	15-33	36.10	3.66
Berks L2P11	1	33-51	13.48	3.68
Berks L2P11	1	>51	8.40	7.43
Berks L2P11	2	0-15	90.95	40.99
Berks L2P11	2	15-33	13.24	13.14
Berks L2P11	2	33-51	10.40	7.76
Berks L2P12	1	0-10	96.55	62.85
Berks L2P12	1	10-28	11.87	17.29
Berks L2P12	1	28-38	14.34	4.88
Berks L2P12	2	0-10	94.25	47.40
Berks L2P12	2	10-28	26.01	3.96
Berks L2P12	2	28-38	9.18	5.17

Buchanan

Buchanan STP Data

Sample identification			Mehlic-1 extractable P	
Plot	app	Horizon depth	Stained sample	Unstained sample
		--- cm ---	--------------- mg/Kg ---------------	
Buchanan L1P1	1	0-5	21.48	12.03
Buchanan L1P1	1	5-24	5.80	5.62
Buchanan L1P1	1	24-34	6.71	5.95
Buchanan L1P1	1	34-58	1.74	0.88
Buchanan L1P1	1	58-86	1.36	0.77
Buchanan L1P1	1	>86	3.27	0.61
Buchanan L1P1	2	0-5	32.24	13.78
Buchanan L1P1	2	5-24	8.12	8.60
Buchanan L1P1	2	24-34	3.64	5.51
Buchanan L1P1	2	34-58	3.64	2.63
Buchanan L1P1	2	58-86	1.54	1.02
Buchanan L1P1	2	>86	1.30	0.60
Buchanan L1P2	1	0-8	34.99	51.20
Buchanan L1P2	1	8-28	39.41	34.15
Buchanan L1P2	1	28-58	11.77	4.46
Buchanan L1P2	1	58-89	7.38	2.22
Buchanan L1P2	1	>89	1.37	0.94
Buchanan L1P2	2	0-8	36.13	26.60
Buchanan L1P2	2	8-28	22.36	32.95
Buchanan L1P2	2	28-58	6.95	4.12
Buchanan L1P2	2	58-89	6.27	3.76
Buchanan L1P2	2	>89	3.86	3.07
Buchanan L2P13	1	0-8	76.60	62.55
Buchanan L2P13	1	8-24	34.04	24.50
Buchanan L2P13	1	24-51	22.87	20.31
Buchanan L2P13	1	51-76	14.34	15.02
Buchanan L2P13	1	>76	12.16	9.28
Buchanan L2P13	2	0-8	53.20	53.15
Buchanan L2P13	2	8-24	35.64	35.90
Buchanan L2P13	2	24-51	20.00	18.92
Buchanan L2P13	2	51-76	18.19	9.12
Buchanan L2P13	2	>76	9.84	6.95
Buchanan L2P14	1	0-10	36.14	42.25
Buchanan L2P14	1	10-23	27.90	22.44
Buchanan L2P14	1	23-36	15.84	17.91
Buchanan L2P14	1	36-51	11.39	13.50
Buchanan L2P14	1	51-94	7.53	3.68
Buchanan L2P14	1	>94	4.42	6.01
Buchanan L2P14	2	0-10	44.79	44.73

Buchanan STP Data Continued

Buchanan L2P14	2	10-23	30.43	24.35
Buchanan L2P14	2	23-36	24.21	22.05
Buchanan L2P14	2	36-51	20.53	17.32
Buchanan L2P14	2	51-94	5.52	4.52
Buchanan L2P14	2	>94	4.30	3.22

Clarksburg

Clarksburg STP Data

Sample identification			Mehlic-1 extractable P	
Plot	app	Horizon depth	Stained sample	Unstained sample
		--- cm ---	--------------- mg/Kg	---------------
Clarksburg L1P6	1	0-13	325.45	340.10
Clarksburg L1P6	1	13-25	42.57	13.03
Clarksburg L1P6	1	25-43	14.75	5.26
Clarksburg L1P6	1	43-69	5.30	0.72
Clarksburg L1P6	1	>69	3.29	0.51
Clarksburg L1P6	2	0-13	259.50	237.00
Clarksburg L1P6	2	13-25	51.40	5.49
Clarksburg L1P6	2	25-43	31.70	4.89
Clarksburg L1P6	2	43-69	19.98	0.94
Clarksburg L1P6	2	>69	11.69	0.81
Clarksburg L1P8	1	0-15	287.35	259.40
Clarksburg L1P8	1	15-36	27.49	5.45
Clarksburg L1P8	1	36-61	2.63	3.03
Clarksburg L1P8	1	>61	1.91	0.68
Clarksburg L1P8	2	0-15	323.65	289.00
Clarksburg L1P8	2	15-36	26.89	19.45
Clarksburg L1P8	2	36-61	5.72	1.56
Clarksburg L1P8	2	>61	1.21	0.63
Clarksburg L2P09	1	0-23	33.01	28.22
Clarksburg L2P09	1	23-53	2.33	1.23
Clarksburg L2P09	1	53-79	0.70	0.36
Clarksburg L2P09	1	>79	0.57	0.48
Clarksburg L2P09	2	0-23	7.97	13.89
Clarksburg L2P09	2	23-53	0.40	0.40
Clarksburg L2P09	2	53-79	0.39	0.52
Clarksburg L2P10	1	0-23	86.35	97.75
Clarksburg L2P10	1	23-53	0.62	0.25
Clarksburg L2P10	1	53-94	0.43	0.25
Clarksburg L2P10	2	0-23	35.19	23.90
Clarksburg L2P10	2	23-53	3.89	1.67
Clarksburg L2P10	2	53-94	0.25	0.54
Clarksburg L2P10	2	>94	0.38	0.52

Appendix 3 ANOVA Output

P results

```
                                         The SAS System        10:02 Friday, October 5,
2007 290

                                       The GLM Procedure

                                    Class Level Information

                     Class            Levels    Values

                     series                3    Berks Buchanan Clarksburg

                     location              2    L1 L2

                     plot                  2    1 2

                     application           2    1 2

                     trt                   2    S U


                             Number of Observations Read         222
                             Number of Observations Used         210
                                         The SAS System        10:02 Friday, October 5,
2007 291

                                       The GLM Procedure

Dependent Variable: p

                                               Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                       10      15007643.64      1500764.36      48.64    <.0001

      Error                      199       6140496.04        30856.76

      Corrected Total            209      21148139.68


                       R-Square     Coeff Var      Root MSE        p Mean

                       0.709644      135.0799      175.6609      130.0422


      Source                      DF        Type I SS     Mean Square    F Value    Pr > F

      series                       2      5610900.304     2805450.152      90.92    <.0001
      location(series)             3      6326622.664     2108874.221      68.34    <.0001
      plot(location)               2        24945.915       12472.958       0.40    0.6680
      application                  1        46322.368       46322.368       1.50    0.2219
      trt                          1        30119.760       30119.760       0.98    0.3244
      depth                        1      2968732.626     2968732.626      96.21    <.0001


      Source                      DF      Type III SS     Mean Square    F Value    Pr > F

      series                       2      5122376.922     2561188.461      83.00    <.0001
      location(series)             2      6610067.625     3305033.813     107.11    <.0001
      plot(location)               2        93941.561       46970.780       1.52    0.2208
      application                  1        89308.621       89308.621       2.89    0.0905
      trt                          1        30119.760       30119.760       0.98    0.3244
      depth                        1      2968732.626     2968732.626      96.21    <.0001
```

```
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                                       The GLM Procedure

         Source                  Type III Expected Mean Square

         series                  Var(Error) + 33.942 Var(location(series)) + Q(series)

         location(series)        Var(Error) + 32.848 Var(location(series))

         plot(location)          Var(Error) + 51.839 Var(plot(location))

         application             Var(Error) + Q(application)

         trt                     Var(Error) + Q(trt)

         depth                   Var(Error) + Q(depth)
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2007 293

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

 Standard Errors and Probabilities Calculated Using the Type III MS for location(series)
as an
                                           Error Term

                                                 Standard                  LSMEAN
               series            p LSMEAN           Error    Pr > |t|      Number

               Berks           370.190517      240.725302      0.2639           1
               Buchanan          3.873074      194.590459      0.9859           2
               Clarksburg       42.285367      229.256259      0.8707           3


                             Least Squares Means for effect series
                              Pr > |t| for H0: LSMean(i)=LSMean(j)

                                     Dependent Variable: p

                         i/j              1             2             3

                            1                      0.5652        0.6512
                            2        0.5652                      0.9911
                            3        0.6512        0.9911
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                                       The GLM Procedure
                                      Least Squares Means

                                                                     H0:LSMean1=
                                          Standard    H0:LSMEAN=0      LSMean2
               trt        p LSMEAN           Error       Pr > |t|       Pr > |t|

               S       150.759105       17.352713         <.0001         0.3244
               U       126.806867       17.352713         <.0001
                                         The SAS System        10:02 Friday, October 5,
2007 295

                                       The GLM Procedure

Dependent Variable: p

        Tests of Hypotheses Using the Type III MS for location(series) as an Error Term
```

```
      Source                        DF     Type III SS     Mean Square    F Value    Pr > F

      series                         2     5122376.922     2561188.461       0.77    0.5634


         Tests of Hypotheses Using the Type III MS for plot(location) as an Error Term

      Source                        DF     Type III SS     Mean Square    F Value    Pr > F

      location(series)               2     6610067.625     3305033.813      70.36    0.0140

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                                    The UNIVARIATE Procedure
                                        Variable:  resid

                                            Moments

                N                          210    Sum Weights                210
                Mean                         0    Sum Observations             0
                Std Deviation       171.407012    Variance            29380.3638
                Skewness            0.17357453    Kurtosis             2.9736672
                Uncorrected SS      6140496.04    Corrected SS        6140496.04
                Coeff Variation              .    Std Error Mean      11.8282076


                                   Basic Statistical Measures

                         Location                    Variability

                     Mean       0.0000     Std Deviation          171.40701
                     Median   -14.2531     Variance                   29380
                     Mode        .         Range                       1190
                                           Interquartile Range    172.10876


                                   Tests for Location: Mu0=0

                        Test           -Statistic-    -----p Value------

                        Student's t    t         0    Pr > |t|    1.0000
                        Sign           M        -8    Pr >= |M|   0.3006
                        Signed Rank    S    -298.5    Pr >= |S|   0.7358


                                      Tests for Normality

                   Test                  --Statistic---    -----p Value------

                   Shapiro-Wilk          W     0.924885    Pr < W     <0.0001
                   Kolmogorov-Smirnov    D     0.113762    Pr > D     <0.0100
                   Cramer-von Mises      W-Sq  0.696818    Pr > W-Sq  <0.0050
                   Anderson-Darling      A-Sq  4.662879    Pr > A-Sq  <0.0050


                                    Quantiles (Definition 5)

                                    Quantile       Estimate

                                    100% Max       615.5416
                                    99%            551.0688
                                    95%            276.3118
                                    90%            174.0435
                                    75% Q3          85.9446
                                    50% Median     -14.2531

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```

```
                    The UNIVARIATE Procedure
                        Variable:  resid

                    Quantiles (Definition 5)

                    Quantile       Estimate

                    25% Q1         -86.1642
                    10%           -140.3128
                    5%            -345.4171
                    1%            -471.7071
                    0% Min        -574.5289


                      Extreme Observations

           ------Lowest-----        -----Highest-----

              Value      Obs           Value      Obs

           -574.529       32         437.085       42
           -559.086       57         447.589       27
           -471.707       36         551.069       46
           -461.204       58         606.353       37
           -413.691       49         615.542       30


                         Missing Values

                                  -----Percent Of-----
          Missing                              Missing
            Value       Count        All Obs       Obs

              .           12         5.41      100.00


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                    The UNIVARIATE Procedure
                        Variable:  resid

   Stem Leaf                                     #             Boxplot
      6 12                                       2                *
      5 5                                        1                0
      5
      4 5                                        1                0
      4 124                                      3                0
      3 67                                       2                0
      3
      2 588                                      3                |
      2 000113                                   6                |
      1 5555677899                              10                |
      1 0001111222223344                        16                |
      0 5555555555666677777777788999999999      34             +-----+
      0 0011111111222333344                     19             |  +  |
     -0 4444444433333333332222111111110         31             *-----*
     -0 9999999999888888777777766666666555555   37             +-----+
     -1 4433332222111111110000000               25                |
     -1 87665555                                 8                |
     -2 4                                        1                |
     -2
     -3
     -3 655                                      3                0
     -4 1100                                     4                0
     -4 76                                       2                0
     -5
     -5 76                                       2                0
        ----+----+----+----+----+----+----+--
    Multiply Stem.Leaf by 10**+2
```

```
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                                    The UNIVARIATE Procedure
                                        Variable:  resid

                                         Normal Probability Plot
                       625+                                                 **
                          |                                               *
                          |
                          |
                          |                                            ***  ++
                          |                                          **  +++
                          |                                           +++
                          |                                        +**
                          |                                     ++***
                          |                                  +++***
                          |                               ++****
                          |                            +*****
                        25+                         +****
                          |                      *****
                          |                 ******
                          |           *******++
                          |         ***  +++
                          |         * +++
                          |        +++
                          |     +++**
                          |  +++ ***
                          |++   **
                          |   **
                          |
                      -575+**
                           +----+----+----+----+----+----+----+----+----+----+
                               -2        -1         0        +1        +2
```

Log P results

```
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                                       The GLM Procedure

                                    Class Level Information

                     Class            Levels    Values

                     series                3    Berks Buchanan Clarksburg

                     location              2    L1 L2

                     plot                  2    1 2

                     application           2    1 2

                     trt                   2    S U


                            Number of Observations Read         222
                            Number of Observations Used         210
                                         The SAS System        10:02 Friday, October 5,
2007 301
```

```
                                       The GLM Procedure

Dependent Variable: log_p

                                               Sum of
      Source                       DF         Squares     Mean Square    F Value    Pr > F

      Model                        10     766.0955220      76.6095522      76.96    <.0001

      Error                       199     198.0825712       0.9953898

      Corrected Total             209     964.1780933

                       R-Square     Coeff Var      Root MSE    log_p Mean

                       0.794558      36.88554      0.997692      2.704833

      Source                       DF       Type I SS     Mean Square    F Value    Pr > F

      series                        2     285.0111905     142.5055952     143.17    <.0001
      location(series)              3     225.2215988      75.0738663      75.42    <.0001
      plot(location)                2       4.3626764       2.1813382       2.19    0.1144
      application                   1       0.0088776       0.0088776       0.01    0.9249
      trt                           1      11.9253941      11.9253941      11.98    0.0007
      depth                         1     239.5657847     239.5657847     240.68    <.0001

      Source                       DF     Type III SS     Mean Square    F Value    Pr > F

      series                        2     294.0992755     147.0496378     147.73    <.0001
      location(series)              2     271.6975078     135.8487539     136.48    <.0001
      plot(location)                2       4.9280585       2.4640293       2.48    0.0867
      application                   1       0.7183607       0.7183607       0.72    0.3966
      trt                           1      11.9253941      11.9253941      11.98    0.0007
      depth                         1     239.5657847     239.5657847     240.68    <.0001
                                         The SAS System        10:02 Friday, October 5,
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                                       The GLM Procedure

         Source                  Type III Expected Mean Square

         series                  Var(Error) + 33.942 Var(location(series)) + Q(series)

         location(series)        Var(Error) + 32.848 Var(location(series))

         plot(location)          Var(Error) + 51.839 Var(plot(location))

         application             Var(Error) + Q(application)

         trt                     Var(Error) + Q(trt)

         depth                   Var(Error) + Q(depth)
                                         The SAS System        10:02 Friday, October 5,
2007 303

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

 Standard Errors and Probabilities Calculated Using the Type III MS for location(series)
as an
                                           Error Term

                                                 Standard                  LSMEAN
               series        log_p LSMEAN           Error    Pr > |t|      Number
```

```
               Berks           4.49985156      1.54334001      0.1003           1
               Buchanan        2.15806563      1.24755993      0.2258           2
               Clarksburg      1.53614225      1.46980959      0.4057           3


                             Least Squares Means for effect series
                              Pr > |t| for H0: LSMean(i)=LSMean(j)

                                   Dependent Variable: log_p

                         i/j              1             2             3

                            1                      0.5666        0.4847
                            2        0.5666                      0.9457
                            3        0.4847        0.9457

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2007 304

                                       The GLM Procedure
                                      Least Squares Means

                                                                     H0:LSMean1=
                                          Standard    H0:LSMEAN=0      LSMean2
               trt    log_p LSMEAN           Error       Pr > |t|       Pr > |t|

               S        2.96965462      0.09855730         <.0001         0.0007
               U        2.49305168      0.09855730         <.0001

                                         The SAS System        10:02 Friday, October 5,
2007 305

                                       The GLM Procedure

Dependent Variable: log_p

        Tests of Hypotheses Using the Type III MS for location(series) as an Error Term

      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      series                       2     294.0992755     147.0496378       1.08    0.4802


         Tests of Hypotheses Using the Type III MS for plot(location) as an Error Term

      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      location(series)             2     271.6975078     135.8487539      55.13    0.0178

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2007 306

                                    The UNIVARIATE Procedure
                                        Variable:  resid

                                            Moments

                N                         210    Sum Weights                210
                Mean                        0    Sum Observations             0
                Std Deviation      0.97353146    Variance             0.9477635
                Skewness           0.65109312    Kurtosis             0.6304836
                Uncorrected SS     198.082571    Corrected SS        198.082571
                Coeff Variation             .    Std Error Mean      0.06718005


                                   Basic Statistical Measures

                         Location                    Variability

                     Mean      0.00000     Std Deviation            0.97353
                     Median   -0.15645     Variance                 0.94776
```

```
                     Mode       .          Range                   5.74731
                                           Interquartile Range      1.24569


                                   Tests for Location: Mu0=0

                        Test           -Statistic-    -----p Value------

                        Student's t    t         0    Pr > |t|    1.0000
                        Sign           M       -21    Pr >= |M|   0.0046
                        Signed Rank    S   -1047.5    Pr >= |S|   0.2357


                                      Tests for Normality

                   Test                  --Statistic---    -----p Value------

                   Shapiro-Wilk          W     0.967503    Pr < W     <0.0001
                   Kolmogorov-Smirnov    D     0.108384    Pr > D     <0.0100
                   Cramer-von Mises      W-Sq  0.453473    Pr > W-Sq  <0.0050
                   Anderson-Darling      A-Sq  2.460916    Pr > A-Sq  <0.0050


                                    Quantiles (Definition 5)

                                    Quantile       Estimate

                                    100% Max       3.096977
                                    99%            2.674442
                                    95%            1.914653
                                    90%            1.358076
                                    75% Q3         0.552897
                                    50% Median    -0.156452

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                                    The UNIVARIATE Procedure
                                        Variable:  resid

                                    Quantiles (Definition 5)

                                    Quantile       Estimate

                                    25% Q1        -0.692793
                                    10%           -1.054203
                                    5%            -1.373225
                                    1%            -1.826591
                                    0% Min        -2.650329


                                      Extreme Observations

                           ------Lowest-----        -----Highest-----

                              Value      Obs           Value      Obs

                           -2.65033       36         2.38523      209
                           -2.05126      155         2.43043      162
                           -1.82659      181         2.67444      152
                           -1.75833      193         2.98583      212
                           -1.66747      165         3.09698       50


                                         Missing Values

                                                 -----Percent Of-----
                          Missing                            Missing
                            Value       Count     All Obs        Obs

                                .          12        5.41     100.00
```

```
                                 Histogram                  #             Boxplot
                 3.25+*                                     1                0
                     .*                                     2                0
                     .***                                   6                0
                     .*****                                10                |
                     .*******                              13                |
                     .***********                          22             +-----+
                 0.25+***************                      30             |  +  |
                     .*********************************    66             *-----*
                     .******************                   35             +-----+
                     .*********                            18                |
                     .***                                   5                |
                     .*                                     1                |
                -2.75+*                                     1                0
                      ----+----+----+----+----+----+---
                      * may represent up to 2 counts

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2007 308

                                    The UNIVARIATE Procedure
                                        Variable:  resid

                                         Normal Probability Plot
                      3.25+                                                  *
                          |                                               * *
                          |                                          *****++++
                          |                                      *****+++
                          |                                   ****++
                          |                               +****
                      0.25+                         +++****
                          |                   *********
                          |             *******
                          |       *******+
                          |   ****+++
                          |+*+++
                     -2.75+*
                           +----+----+----+----+----+----+----+----+----+----+
                               -2        -1         0        +1        +2
```