ABSTRACT

Title of Dissertation: EVALUATION OF THE ACCURACY AND SENSITVITY OF THE UNIVERSITY OF MARYLAND PHOSPHORUS MANAGEMENT TOOL AND INVESTIGATION OF SUBSURFACE PHOSPHORUS DYNAMICS IN THE MARYLAND COASTAL PLAIN REGION

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Phosphorus (P) loss from agricultural fields to surface water represents a major environmental challenge in agricultural nutrient management. To reduce P loading, areas where both P source and transport conditions are present must be identified and appropriate management practices implemented to reduce the source or break transport connectivity. The Maryland P Site Index (MD-PSI) was modified from a multiplicative structure to a component structure and renamed University of Maryland Phosphorus Management Tool (UM-PMT). In the UM-PMT, each component is the product of source, transport, and management factors specific to a P loss pathway. Our objectives were to evaluate the UM-PMT for accuracy, investigate soil conditions in ditch-drained agricultural systems, compare different methods for degree of P saturation (DPS) calculation, and compare numerical and categorical final scores of the multiple versions of the Maryland P loss risk indices. Agronomic soil samples were collected from fields across Maryland, and analyzed for P, aluminum (Al), and iron (Fe) concentration using multiple extractions, soil texture was determined, and degree of P saturation (DPS) was calculated using five methods. Deep soil samples were collected and analyzed similarly from three sites on Maryland's eastern shore. A poor relationship was identified between UM-PMT and modeled P loss data (R^2=0.09), but the relationship improved with modifications to UM-PMT calculation (R^2=0.97), which resulted in UM-PMT Version 2 (UM-PMT v.2). Soil Fe concentration was responsible for a large proportion of DPS at one sample location on the Eastern Shore, demonstrated through poor correlation between two methods for DPS calculation, including and excluding Fe concentration. Numerical differences existed between different methods for DPS calculation and these translated to differences in UM-PMT final score, particularly in the Lower Shore region. The UM-PMT v.2 categorized more fields as HIGH risk than MD-PSI but less than UM-PMT. Neither version of the UM-PMT was very sensitive to management factor input variables. Evaluation of tools like the UM-PMT for accuracy, sensitivity, and magnitude of change is necessary to understand potential economic and environmental impacts of implementing new indices as nutrient management tools.

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by

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1.1 Introduction

Phosphorus (P) is an essential plant nutrient and, along with nitrogen (N) and other essential nutrients, is routinely applied to crops and pastures to increase plant growth and quality. These nutrients can be applied as inorganic sources, such as commercially produced fertilizers, or organic sources, such as animal manures. Nutrient application rate is determined based on the amount of nutrient sufficient to optimize crop performance.

Phosphorus and N loss to surface water from point or non-point sources can contribute to eutrophication, which is a major problem globally. Eutrophication, or enrichment of surface water with nutrients, leads to a surge of aquatic plant growth, which is typically limited by nutrients such as N and P. As the aquatic plants die, respiration by decomposing organisms consumes dissolved oxygen, causing aerobic habitats to become anaerobic, leading to fish kills and low aquatic biodiversity.

Both N and P are nutrients of concern, but they behave and are managed differently in the environment. Nitrogen is very soluble and easily transported with water. Typically, N not taken up by a growing crop is susceptible to environmental loss, either to the atmosphere or to nearby surface water. A common mitigation strategy is to apply N at rates and timing that match uptake of the growing crop. Additionally, N can be applied in more soluble forms that maximize plant uptake and minimize environmental loss.

Adjustment of N application rates can effectively increase use efficiency (relative proportion of N applied compared to N removed by crops) and decrease N loss to the environment. Phosphorus, however, exists as multiple forms within the soils, differing in their availability for crop uptake. Crops are able to uptake P that exists in the soil solution in available forms such as P found in inorganic fertilizers. Phosphorus can be added to the soil solution once mineralized from organic P forms, which originate from plant residue and animal manures. Additionally, P can precipitate into secondary compounds, like calcium- or aluminum-phosphates, which require dissolution for P to become plant available. Phosphorus is adsorbed to clay minerals in the soil. It typically forms a stronger bond to the clay surface than other cations found in the soil solution, due to the attraction between negatively-charged phosphate ions and the positively charged ions that comprise the structure of the first layer of the clay particle. This attraction is stronger than other cations to the clay surface, as other cations in the soil solution are attracted to the negative charges nearer to the clay surface. This stronger adsorption of P to clay surface makes it difficult for growing crops to remove the P they require from the clay surface, the P must be present in the soil solution pool to maximize plant uptake.

Historically, application of P beyond crop requirements was not thought to pose any environmental risk due to the relative immobility of P in soil and the lack of known toxicities associated with elevated soil P concentrations. It was widely accepted that measures to control soil erosion would also control P loss. Where animal manures are used to fertilize crops, they are typically applied at rates needed to meet the N requirement of the crop. Due to the low N:P ratio of manure, this can result in application of P at rates well beyond the crop requirement. Soils have a finite sorption capacity for P and as P saturation increases, it is possible for P to desorb from soil particles under an appropriate P concentration gradient. This dissolved P (DP) can be easily moved with water, both across the soil surface or along with subsurface lateral flow.

1.2 Conditions in Maryland

Eutrophication is an especially important issue in the state of Maryland, as the state surrounds the Chesapeake Bay, the largest estuary in the United States. The watersheds that drain into the Bay cover 64,000 square miles (165,760 square km) of land within six states and the District of Columbia (CBP, 2012). Agriculture is one of the largest contributors of nutrients to surface water, mostly due to large number of acres within the Bay watershed devoted to agriculture. In Maryland alone there are 6.25 million acres of agricultural land (NASS, 2007).

Water quality in the Chesapeake Bay and its tributaries exhibited significant decline in the 20th century. To address nutrient loss and improve water quality, the Maryland General Assembly passed the Water Quality Implementation Act (WQIA) in 1998 (Coale et al., 2002). One method for controlling nutrient loss that was outlined in the WQIA was the use of comprehensive nutrient management plans on agricultural operations to record and manage the nutrients applied to fields by producers. Fields with high soil P concentration are first evaluated for the risk of P loss from agricultural fields to surface water. Once risk of P loss is assessed, producers will follow P management recommendations based on the level of risk of P loss. The P Site Index (PSI) was implemented as the nutrient management tool to identify fields with risk of P loss to surface water (Coale et al., 2002).

1.3 Phosphorus Index

Both a P source and a transport mechanism must be present in a field for the field to contribute to P pollution. Sources of P may be fertilizer, manure, or elevated soil P concentrations. Transport mechanisms include erosion, runoff, or subsurface leaching (Djodjic et al., 2002; Gburek and Sharpley, 1998; Lemunyon and Gilbert, 1993). The parts of a field or landscape where these two factors exist simultaneously are referred to as critical source areas (Djodjic and Bergström, 2005; Djodjic et al., 2002; Sharpley et al., 2003) and it has been shown that only a small percentage of an entire watershed contributes to the total amount of P lost to a body of water in certain landscapes (Gburek and Sharpley, 1998; Gburek et al., 2000; Sharpley et al., 2001).

The PSI was developed in the United States in 1993 to identify regions of a watershed or field that are at risk for contributing P to surface water (Djodjic et al., 2002; Lemunyon and Gilbert, 1993; Mallarino et al., 2002; Sharpley et al., 2003). The goal of the PSI was to target specific fields or areas within a field that had the highest risk for discharge of P to surface water in order to focus mitigation efforts on these areas (Bechmann et al., 2009; Djodjic et al., 2002; Lemunyon and Gilbert, 1993). The PSI was designed as an indexing tool for use by field extension agents, planners, or even producers themselves to identify CSAs in fields or watersheds (Lemunyon and Gilbert, 1993; Sharpley et al., 2001). It was designed to be simple and user-friendly by requiring minimal data from the producer, such as use of various management practices or timing of manure application (Djodjic and Bergström, 2005; Gburek et al., 2000; Lemunyon and Gilbert, 1993). Phosphorus Site Index factors include management practices, soil type, climate, and crop management, which can be modified by region for more accurate risk assessment (Djodjic and Bergström, 2005).

In earlier versions of the PSI, the weighted values for all transport and source factors were summed separately. The risk for P loss from the site was calculated by multiplying numerical risk factors for source by those for transport (Lemunyon and Gilbert, 1993). This ensured that both high transport risk and high source risk were present for the final PSI score to be high. Some source or transport variables are multiplied by a weighing factor, as some factors are more important for P movement than others.

Equation 1.1 Equation for the Maryland Phosphorus Site Index

$$PSI = A * B$$
$$Where$$
$$A = 0.02 * [(2 * RUSLE) + RUNOFF + SUBSURFACE + LEACHING + DISTANCE + WATERSHED]$$
$$AND$$
$$B = (0.2 * FIV) + FR + FM + OR + OM$$

Equation 1.1 shows the Maryland PSI (MD-PSI; (Coale, 2008)) where A represents the transport risk factors, including erosion estimated using the revised universal soil loss equation (RUSLE), surface runoff (RUNOFF) determined by a matrix of soil permeability class and slope, subsurface drainage class (SUBSURFACE) determined by a matrix of soil drainage class and depth to seasonal high water table, leaching potential (LEACHING) determined by a matrix of Maryland NRCS leaching value and depth to seasonal high water table, distance from edge of field to surface water (DISTANCE), and priority of receiving water (WATERSHED). Within Equation 1.1, B represents the source factors, including fertility index value (FIV), which converts soil P concentrations obtained from various testing laboratories to standardized values for comparison (McGrath, 2006).The source factors for the MD-PSI also include P fertilizer application rate (FR), P fertilizer application method (FM), organic P application rate (OR), and organic P application method (OM).

1.3.1 Transport Factors

It has been recommended that a PSI include erosion, runoff class or potential, subsurface drainage, contributing distance, modified connectivity, priority of receiving watershed, irrigation erosion, and return period as transport factors (Gburek et al., 2000;

Lemunyon and Gilbert, 1993; Sharpley et al., 2008; Sharpley et al., 2003). Erosion is typically predicted using RUSLE (Equation 1.2) and is reported as tons of soil loss per acre per year (Lemunyon and Gilbert, 1993; Renard et al., 1997).

Equation 1.2 Revised Universal Soil Loss Equation (RUSLE, Renard et al. 1997)

$$RUSLE = R * K * C * P * LS$$

The RUSLE score incorporates site and soil characteristics, crop rotations, and additional practices, such as tillage or contour planting. This calculation can be performed by hand or with the aid of a computer program and requires knowledge of management practices and crop rotations used on the operation. Since erosion is the primary pathways by which P can be lost from fields, the RUSLE score is multiplied by two in the MD-PSI.

Runoff class or potential was included in the MD-PSI because runoff can carry DP across field surfaces (Sharpley et al., 2003). The information for this factor can be determined from soil survey data (Lemunyon and Gilbert, 1993). Subsurface drainage is a less common transport pathway, however in areas with sandy soils or soils that are saturated with P, it is possible that P can move vertically down through the soil profile (NC-PLAT, 2005; Sharpley et al., 2003). This mechanism of transport is important in the mid-Atlantic region, where these conditions exist, and states such as Maryland, Delaware, and North Carolina have included some subsurface transport factor in their PSIs (Buda et al., 2009; NC-PLAT, 2005; Shober and Sims, 2013).

Irrigation erosion is included as a factor in the MD-PSI and it determines the likelihood that soil particles will detach from soil surface when irrigation is applied (Lemunyon and Gilbert, 1993). The MD-PSI also includes a factor that ranks receiving water bodies and increases ranking for water bodies with poorer water quality (Sharpley et al., 2003). Contributing distance is the distance from the edge of the field to the closest body of surface water; therefore, fields closer to a body of water have higher risk for P loss to surface water than those at a greater distance from water (Sharpley et al., 2008). Contributing distance can be directly linked to return period, as this may be the best way to rank contributing distance. Depending on the length of the return period, the area of a watershed that will contribute water (and potentially P) to a watershed changes; as the return period gets shorter, there is a smaller area of a field that can contribute P to a body of water (Sharpley et al., 2008).

1.3.2 Source Factors

While the soil acts as a large source of P available for loss to surface water, P amendments applied to a field are also at risk for loss to surface water (Gburek et al., 2000; Lemunyon and Gilbert, 1993; Sharpley et al., 2008; Sharpley et al., 2003). Soil test P (STP) has been measured using multiple extractions methods through time, as extraction techniques have been updated. Some examples of soil extractants include ammonium acetate, Bray solution (Bray and Kurtz, 1945), Olsen solution (Olsen et al., 1954), Mehlich 1 (Mehlich, 1978), and Mehlich 3 (Mehlich, 1984). Some extractants are more appropriate for measuring certain nutrients, while other extractants are more suitable for specific regions of the US, due to regional differences in soil condition (Gartley et al., 2002). Even when the same extractant is utilized, difference in soil type can affect results, as well as differences in methodology used by individual laboratories (i.e. volume vs. mass, scoop vs. weighing) (Gartley et al., 2002). It can often be difficult to compare soil test results performed in different laboratories or using different extractants, and these differences in soil extractants are also found in P indices across the US. Maryland and Delaware convert Mehlich-3 extractable soil nutrient concentrations to a fertility index value (FIV), which represent the STP factor in the MD-PSI (Coale et al., 2002; Sharpley et al., 2008).

Phosphorus in amendments, such as inorganic fertilizers and animal manures, exist in forms with varying availability for plant uptake. Inorganic P fertilizers contain P that is available for plant uptake whereas organic amendments contain some P that must be mineralized before becoming available for plant uptake. In addition to the variety of P forms in P amendments, the method for P application, including timing of application, can also alter the availability of the P source. Generally, incorporation of P amendments can decrease risk of P dissolving from the amendment and being transported to surface water, by mixing P from the amendment with soil particles. Incorporation immediately following amendment application decreases risk of precipitation interacting with the amendment, dissolving P, and transporting the DP in runoff.

1.4 Justification for Modifications to the Maryland Phosphorus Site Index

Modifications to the MD-PSI have occurred since its inception to include new technology and knowledge gained since its initial development. Recent research has evaluated the benefits of transitioning from multiplicative indices, such as the MD-PSI, to a component structure (Bolster et al., 2011). A component index utilizes individual components meant to represent major P loss pathways and each component is comprised of source and transport factors unique to that loss pathway. Therefore, in areas where one loss pathway is responsible for a large quantity of P loss, one component will have a large score relative to the other components. This will allow the end-user of the PSI to better understand how P could be potentially lost from each specific field and on which fields to focus mitigation strategies. Certain management practices can be implemented that will decrease P loss from one loss pathway, therefore, in addition to pathway-specific transport and source factors, pathway-specific management options can be included for each loss pathway. A component PSI structure should encourage adoption of desirable management practices, as the end-user can understand how management practices will lower PSI score and mitigate potential P loss.

Each component of PSI with this type of structure represents a transport pathway whereby P can be lost to surface water, and should include particulate and surface runoff pathways. In MD and other Mid-Atlantic coastal plains regions, subsurface loss of DP can also be a major route for P loss to surface water and should also be included as a component of a PSI.

1.5 Phosphorus Loss Pathways

1.5.1 Particulate-Bound Phosphorus Movement

Phosphorus has an affinity for adsorption to Fe- and Al-hydroxide ions within the outer layers of clay particles. Particulate-bound P loss describes P that does not dissociate from the soil particle while the entire particle is carried from the field to surface water. This particulate-bound P is the form in which the greatest quantity of P is lost from agricultural fields in most areas of the US. Soil erosion typically occurs in areas with sloping landscapes and low crop cover, which allows runoff to flow quickly across the soil surface. As runoff moves across soil surface, there is a greater risk that soil particles will be dislodged and travel with flowing water. Besides the installation of terraces, the slope of a field generally cannot be modified. However, other management options, such as maintaining good vegetative cover, can be implemented to slow the flow of water across a field to decrease soil erosion. Maintenance of crop residues through reduced tillage can slow the flow of water across the soil surface and act as a barrier to prevent movement of soil particles from the field. Contour planting, that is planting crops so rows are perpendicular to flow of water down a slope, can also help prevent erosion in areas with steep slopes. Implementation of management practices to reduce erosion is the most effective means of reducing loss of particulate-bound P.

1.5.2 Surface Transport of Dissolved Phosphorus

Due to the strong attraction between phosphate molecules and the clay surface, the dissolved pool of P in most soils is often small and typically considered less often than particulate-bound P when assessing P loss to the environment. However, DP that is delivered to surface water can be more detrimental to water quality than particulate-bound P, as the DP is already present in a form that can be readily utilized by aquatic vegetation or microorganisms. Particulate-bound P that is deposited in surface water must first desorb from the soil particle before it can be utilized by aquatic vegetation. In soils with low clay content that are saturated with P, the addition of P amendments can lead to elevated concentrations of dissolved P in the soil (King et al., 2014). Dissolution of soil P minerals, desorption from the mineral P pool, hydrolysis of organic P compounds, or direct transport of phosphate-P found in manures or the soil solution can be sources of DP. When DP moves across soil surface with runoff, it could infiltrate through the soil and become adsorbed to clay particles. However, with recent P applications, the surface soil particles may be temporarily saturated with P, which increases the risk of DP loss to surface water.

To mitigate loss of DP to surface waters, producers can incorporate P amendments that are surface applied into the soil, to increase adsorption of P to soil surface. The recommendation for decreasing loss of DP opposes the recommendation to decrease loss of particulate-bound P in some cases. A decision must be made by the producer as to which P loss pathway is driving P loss in their specific field. From this knowledge they must decide which management option will work for their operation to minimize P loss.

1.5.3 Subsurface Loss of Dissolved Phosphorus

Subsurface P losses are typically associated with agricultural systems that utilize artificial drainage to lower the water table. Artificial drainage systems have been used for centuries for the basic purpose of controlling water (Needelman et al., 2007; Shirmohammadi et al., 1995). Low areas, where water has the tendency to pond, marshes, wetlands, or peat bogs are all examples of areas where artificial drainage is used to control groundwater levels. One of the most common uses for artificial drainage systems in the US today is to create suitable conditions for agricultural production.

Artificial drainage is a common practice on the Delmarva Peninsula and may be necessary for agricultural production in this area. The Delmarva Peninsula has sandy Coastal Plain soils and high water tables. Without artificial drainage to lower the water table, southern areas of the peninsula could have ponding or water tables very near to the surface for most of the year. Ditches and tile drains are two types of artificial drainage used on the Delmarva Peninsula.

In fields with artificial drainage, the presence of the ditches adjusts the water table so that it is at its lowest point in the ditch and the highest point in the middle of the field between the bordering ditches. This generates a water table gradient that promotes lateral movement of soil water from the field to the ditch that could be rapid in more coarse soil types (Needelman et al., 2007). When nutrients or compounds move vertically downwards through the soil profile and interact with the water table, they are at risk for being quickly shuttled to ditches and eventually to main bodies of water. Additionally, during the winter water table maxima, any Fe-hydroxides in soils can become reduced, decreasing soil affinity for P, which can release P to the shallow groundwater (Sims et al., 1998).

Subsurface nutrient loss is typically associated with more mobile nutrients such as N; however, it is possible for P to be lost through subsurface flow through a soil where specific conditions are present. Subsurface P loss is more likely to occur in sandy, well-drained soils, soils with high organic matter, or soils saturated with P (King et al., 2014). In a sandy soil with little clay, there are fewer Fe and Al ions present to adsorb P ions. In a soil with high organic matter, there are also fewer Fe and Al ions available for P adsorption, therefore P is less likely to be retained in the soil.

In fields where these contributing factors exist, especially P saturated soils, there is a high risk for P loss. Not only does the concentration gradient favor P desorption from the soils, there are multiple pathways for shuttling this DP through the soil to shallow groundwater that is well-connected to artificial drainage through horizontal flow (Sims et al., 1998). Dissolved P can also move through preferential flow pathways (King et al., 2014). Dissolved P moving through matrix flow, or through the soil profile, moves slowly and is likely to interact with clay particles or Fe- and Al-hydroxides to adsorb DP before its delivery to surface or groundwater. In numerous studies however, subsurface P loss was found in soil conditions where subsurface loss would not have been predicted, and in these situations, preferential flow pathways were responsible for delivery of DP (Heathwaite and Dils, 2000; Simard et al., 2000). Preferential flow pathways include root channels or earthworm burrows which shuttles water very quickly into deep layers of the soil profile. When this water contains nutrients, those also move quickly through the soil. These pathways present a problem because there is very littler nutrient interaction with potential sorption sites in the soil (Fraser et al., 2001; Nelson et al., 2005). These pathways typically occur in more structured soils with high clay content, where the channels can remain intact for longer period of time (Bergstrom et al., 2001). Soils with more 2:1 layer clays that shrink and swell under changing moisture conditions also form large cracks that act as preferential flow pathways (Bergstrom et al., 2001). Preferential flow pathways also tend to be more common in fields using no-till or reduced tillage practices (Shipitalo and Gibbs, 2000). Although no-till practices are recommended to reduce soil and nutrient loss due to erosion, some tillage may be recommended in fields where preferential flow pathways are the route for soil and nutrient loss, in order to break pathways and increase P adsorption to clay in the soil profile (Feyereisen et al., 2010; Kleinman et al., 2009; Sims et al., 1998).

1.6 University of Maryland Phosphorus Management Tool

The University of Maryland Phosphorus Management Tool (UM-PMT) is a restructured version of the MD-PSI, where the equation has been changed from a multiplicative to a component structure. The three components of the UM-PMT represent the particulate bound-P, surface DP, and subsurface DP loss pathways, including specific source, transport, and management factors.

Most input variables remained the same between the two versions of the MD P loss risk indices. Two variables used in the MD-PSI that are not included in the UM-PMT are the priority of receiving water body and the leaching factor. The priority of receiving water factor was removed, as it has been determined that P discharge should be minimized in all receiving water bodies within Maryland. The leaching factor has also been removed from the MD-PSI, as it is no longer available through soil surveys and it would be redundant within the SUBSURFACE component (McGrath et al., 2013).

Equation 1. outlines the UM-PMT equation and each component will be discussed in detail, with source, transport, and management variables outlined.

Equation 1.3. Equation for the University of Maryland Phosphorus Management Tool

$$UMPMT = 0.1*(PARTICULATE + RUNOFF + SUBSURFACE)$$

$$\text{Where}$$

$$PARTICULATE = DBF * SED * FIV$$

$$RUNOFF = DBF * SR * DPR_r$$

$$SUBSURFACE = SD * DPR_{sub}$$

1.6.1 PARTICULATE Component of the University of Maryland Phosphorus Management Tool

The PARTICULATE component of the UM-PMT represents the risk of P loss due to particulate-bound P forms (McGrath et al., 2013). The sediment risk transport factor (SED) is a categorical value assigned to a range of RUSLE values (Table 1.1). The source factor for the PARTICULATE component is soil test P concentration, reported as FIV. Management practices used to reduce particulate-bound P loss are contained within the RUSLE calculation. As crop rotations or tillage practices are adjusted, the RUSLE score will change accordingly. The distance buffer factor (DBF), is the multiplication of the distance factor (DF) and the buffer factor (BF). The DBF is applied to both the PARTICULATE and RUNOFF components of the UM-PMT, as the risk of P loss through these pathways is decreased the further the field is from water (McGrath et al., 2013).

1.6.2 RUNOFF Component of the University of Maryland Phosphorus Management Tool

The RUNOFF component of the UM-PMT represents surface DP loss from both amendments and soil as sources (McGrath et al., 2013). The transport factor of the RUNOFF component is the surface runoff (SR) transport matrix, comprised of soil permeability class and slope (Table 1.). The runoff dissolved P risk (DPR_r) factor includes degree of P saturation (DPS) multiplied by two as the soil source and the water soluble P application factor (WSP_{app-r}) as manure source (Equation 1.4).

Equation 1.4 Dissolved P Source (DPR) variable of the Runoff Component

$$DPR = WSP_{app} + (2 * DPS_{M3})$$
$$\sum_0^n WSP_{app-r} = \sum_0^n PSC * TP * AM_r$$

The amendment P source factor (WSP_{app-r}) is the application rate of the amendment applied (TP) multiplied by the P solubility coefficient (PSC; Table 1.3), which considers the solubility of P within various animal manures and P amendments. The amendment P source is multiplied by the application method (AM_r) factor (Table 1.4), which lowers the P source value where better management practices are implemented. As previously mentioned, management practices which incorporate amendments into the soil will increase the contact between soluble P and clay surfaces and Fe- and Al-hydroxides, to increase the proportion of DP that is adsorbed to soil particles and decrease DP loss to surface water.

1.6.2.1 Degree of Phosphorus Saturation

The DPS has been included in the UM-PMT as the P source for the RUNOFF component. The results of standard soil tests represent the concentration of nutrients in the soil that are available for plant uptake, as fertilizer recommendations are made based on these results. However the goal of the P index is to assess risk of P loss to the environment, meaning agronomic soil test results may not represent the concentration of P that could potentially be lost to surface water (Pautler and Sims, 2000). Degree of P saturation is a more appropriate measure of soil P that can be lost to surface water, as soil P, Al, and Fe concentrations are accounted for in the calculation. Since P is often found adsorbed to Fe or Al, DPS relates the concentration of P in the soil relative to the concentration of Fe and Al. As the concentration of P increases compared to the concentration of Al and Fe, there is a greater risk of P saturation of Al and Fe ions and loss of P from the soil (van der Zee and van Riemsdijk, 1988).

One method for DPS calculation requires extraction of a soil sample with ammonium oxalate and measurement of P, Al, and Fe concentrations (P_{ox}, Al_{ox}, Fe_{ox}; Equation 1.5, (Schoumans, 2000)).

Equation 1.5 Calculation of degree of P saturation using ammonium oxalate extraction

$$DPS_{ox}(\%) = ([P_{ox}] / PSC_t) * 100$$
$$PSC_t = \alpha([Al_{ox}] + [Fe_{ox}])$$

The total P sorption capacity (PSC_t) factor in Equation 1.5 represents the total P sorption capacity of a soil sample. The alpha value is an empirical parameter calculated as the sum of P_{ox} and PSC_r, or the remaining sorption capacity of the soil, divided by the sum of Al_{ox} and Fe_{ox} (Equation 1.6).

Equation 1.6 Calculation of alpha value within DPS calculation

$$PSC_t = [P_{ox}] + PSC_r$$
$$PSC_t = \alpha([Al_{ox}] + [Fe_{ox}])$$
$$\downarrow$$
$$[P_{ox}] + PSC_r = \alpha([Al_{ox}] + [Fe_{ox}])$$
$$\downarrow$$
$$\alpha = \frac{[P_{ox}] + PSC_r}{[Al_{ox}] + [Fe_{ox}]}$$

The PSC_r is determined by fitting isotherm data to a nonlinear line of best fit using a number of available equations, including the Langmuir and Freundlich equations (Sparks, 2003). These equations are used to describe the quantity of adsorption, specifically the adsorption of phosphate molecules to solid soil surface in solution (Mead, 1981; Sparks, 2003). These equations were initially used to describe other phenomena but have been found to describe adsorption kinetics of phosphate molecules and therefore were adopted for use in soil chemistry (Sparks, 2003). Both the Freundlich and Langmuir equations are empirical models, which do not explain mechanisms for adsorption (Sparks, 2003).

No adsorption model is better than another per se, as both have more appropriate uses. The Langmuir equation can be used to calculate an adsorption maximum, however the model relies on the assumption of uniform surface adsorption (Sparks, 2003), as it was created to describe the adsorption of gas onto planar surfaces. The Freundlich model considers surface heterogeneity, which may be more appropriate for soil colloids (Sparks, 2003), but has been shown experimentally to better predict phosphate adsorption in soils when a measure of native adsorbed phosphate is provided (Sparks, 2003).

To calculate an alpha value, sorption isotherms must first be performed on soil samples (Nair et al., 1984). Sorption isotherms entail equilibrating a soil sample in a range of known P concentrations and measuring the concentration of P remaining in each solution after a determined equilibration time at a constant temperature. Concentrations of P added to the soil are plotted versus P concentrations measured in the sample after equilibration time then one of the adsorption models must be fit to the data to determine the sorption capacity (PSC_r) of the soil (Nair et al., 1984). It can be time consuming to iteratively fit a nonlinear best fit line to the data and a common practice is to use a linearized form of the Langmuir equation to more easily fit a line to the data points (Bolster and Hornberger, 2007). While this may be a quicker method for fitting data, there may be a good fit observed with a linearized version of the equation that is not observed with the nonlinear equation. If the parameters determined with the linearized equation are not confirmed with the nonlinear equation, a poor estimate of parameters may be masked by the good fit seen with the linearized equation (Bolster and Hornberger, 2007). Scientists at USDA-ARS have created a Microsoft Excel spreadsheet to optimize fitting of non-linear models to isotherm data for multiple adsorption models (Bolster, 2008). Since performance of isotherms and fitting of adsorption equations to isotherm data is time consuming, a standard alpha value of 0.5 is commonly used in the Mid-Atlantic region, as this was found to be the mean alpha value in studies using similar acid sandy soils (Lookman et al., 1995; Pautler and Sims, 2000).

Despite being the original method for calculation of DPS, P sorption isotherms and ammonium oxalate extraction are rarely used in soil testing laboratories. The ammonium oxalate extraction must be completed in darkness and calculation of alpha values can be time consuming and it is not practical to perform these experiments on a large volume of samples. Instead, soil testing laboratories in the Mid-Atlantic region utilize Mehlich-3 extraction, as it provides a more accurate estimation of plant-available nutrients (Mehlich, 1984). The Mehlich-3 phosphorus saturation ratio (M3PSR-I) can be calculated as an alternative measure of P saturation in soils using Mehlich-3 extractable concentrations of P, Al, and Fe (M3P, M3Fe, M3Al; Equation 1.7).

Equation 1.7 Mehlich 3 Phosphorus Saturation Ratio-I (M3PSR-I)

$$M3PSR-I=\frac{[M3P]}{[M3Al]+[M3Fe]}$$

The M3PSR-I was adapted from M3P saturation index developed for acid, sandy soils in Canada (Khiari et al., 2000). The M3P saturation index (M3PSR-II; Equation 1.) only included M3Al in the denominator of the equation, as it had been suggested that soil Al concentration is responsible for most P adsorption.

Equation 1.8. Mehlich 3 Phosphorus Saturation Ratio-II (M3PSR-II)

$$M3PSR-II=\frac{[M3P]}{[M3Al]}$$

The M3Fe concentration in the M3PSR-I calculation may not be necessary, as a nearly perfect relationship has been demonstrated between M3PSR-I and M3PSR-II (Khiari et al., 2000; Sims et al., 2002). Additionally, Sims et al. (2002) identified a linear relationship between M3-PSR and DPS_{M3} (Equation 1.) and this equation is utilized in the UM-PMT to calculate DPS (McGrath et al., 2013).

Equation 1.9. Linear conversion from Mehlich 3 P saturation ratio to degree of P saturation via oxalate extraction method (DPS_{M3})

$$DPS_{M3}=\frac{(M3PSR)+0.019}{0.0042}$$

1.6.2.2 Phosphorus Source Coefficients

Phosphorus source coefficients (PSC) have been implemented to weight the solubility of P from various amendments applied to agricultural fields (Coale et al., 2005; Elliott et al., 2006; Leytem et al., 2004). Amendments with more soluble forms of P, such as inorganic fertilizers, have higher PSC values, with animal manures having less soluble forms of P and therefore lower PSC values (Table 1.3). Treated manures, such as poultry litter from animals fed phytase or biosolids treated with Fe to bind P, further decrease the solubility of P resulting in a lower PSC value.

The equation for calculating PSC for organic amendments has been modified from the MD-PSI to the UM-PMT equation. The equation used in the UM-PMT ($PSC=0.117*WEP_{100}$) is used to calculate the PSC of an amendment where the water extractable P concentration of the amendment has been measured using a 100:1 water extraction method (Elliott et al., 2006).

1.6.3 SUBSURFACE Component of the University of Maryland Phosphorus Management Tool

Finally, the SUBSURFACE component of the UM-PMT assesses the risk of DP loss through subsurface pathways (McGrath et al., 2013). The SUBSURFACE component is only calculated in fields where artificial drainage is present. If no artificial drainage is present in the field, the SUBSURFACE component score defaults to zero in the UM-PMT (McGrath et al., 2013). The source factor for the SUBSURFACE component is the dissolved P risk (DPR_{sub}) factor, which is calculated almost identically to the DPR_r factor in the RUNOFF component (Equation 1.4), with differences in the application management factor (AM_{sub}; Table 1.5), as the management practices included in the SUBSURFACE component are different from the RUNOFF component.

The transport factor for the SUBSURFACE component is a matrix of soil drainage class and hydrologic soil group (Table 1.). Both measures are similar, as soil drainage class is the amount of time the soil is under saturated conditions (Soil_Survey_Division_Staff, 1993) and hydrologic soil group is determined by the depth of the soil layer with the lowest saturated hydraulic conductivity (NRCS, 2007). In a soil type where drainage is poor and restrictive soil layer is closer to the surface, the water table may be close to the surface but water may not infiltrate quickly through the profile. This scenario represents a high risk for P loss to ditches, especially coupled with soils with high P saturation. Similar scenarios exist where drainage is good, as water will move quickly through the profile to shallow groundwater, which carries water and soluble P horizontally to a nearby ditch.

1.6.4 Final Score of the University of Maryland Phosphorus Management Tool

After calculation of the three UM-PMT components, the scores for each component are summed and multiplied by a scaling factor of 0.1. The numeric score falls within one of the interpretive categories (Table 1.7) outlining the management practices to be implemented.

1.7 Evaluation of Phosphorus Indices

The use of a PSI as a nutrient management tool prompted an investigation of a standardized method for evaluation of P indices. Recommendations from the Southern Extension-Research Activity Group 17 (SERA-17) outline that PSIs should be evaluated against local, measured P loss data to establish upper thresholds based on local water quality conditions (Sharpley et al., 2011). Collection of measured P loss data can be expensive and time consuming, and is typically not readily available. The SERA-17 recommendations continue to note that modeled P loss data may be used where measured data does not exist and the model used to generate the data must provide a reasonable estimate of P loss from the field (Sharpley et al., 2011). If an appropriate model has already been developed and validated for a state or region, it should be used for the evaluation. For the evaluation of the UM-PMT, modeled P loss data was generated using the Annual P Loss Estimator (APLE) model (Vadas, 2012a).

The APLE model is field-scale P loss quantification model that runs on an annual time step (Vadas, 2012a). The APLE model quantifies P loss, unlike most PSIs across the country which rank relative risk for P loss to the environment. The APLE model quantifies P loss through erosion and DP lost through surface runoff, but does not include any subsurface P loss pathways. Management strategies as well as organic and inorganic P applications are considered, similar to a PSI, however the APLE model also accounts for organic P application through manure deposition from grazing animals. The APLE model uses easily obtained inputs and is user friendly, similar to a PSI, but requires additional input variables including annual precipitation and runoff, soil organic matter content, and clay percentage (Vadas, 2012a). The APLE model can be distributed into three components for ease of comparison to the UM-PMT equation, all with units of kg P ha^{-1}: sediment P loss, soil dissolved P loss, and manure dissolved P loss.

The sediment P loss component of APLE is the product of soil total P concentration, annual sediment loss, and an erosion enrichment ratio. Soil total P concentration is the sum of soil labile P, active P, stable P and organic P, all of which are calculated based on soil test P concentration, clay, and organic matter content that is entered by the user. Annual sediment loss is entered as tons of sediment lost per acre per year from RUSLE then converted from tons acre^{-1} to kg ha^{-1}. The erosion enrichment ratio is a unitless ratio of total P in eroded sediment to P concentration in the soil (Vadas, 2012a).

The soil DP loss component of APLE is the product of soil labile P concentration, an extraction coefficient, and annual runoff (Vadas, 2012a). Soil labile P concentration is calculated as half the M3P concentration of the soil, the extraction coefficient equals 0.005, and the amount of annual runoff is entered in inches, as it is commonly reported, but is converted to L ha^{-1} then multiplied by 10^{-6} to result in unit of kg ha^{-1} (Vadas et al., 2005; Vadas, 2012a).

Finally, the manure and fertilizer dissolved P components of the APLE model are similar and will be discussed together. Both components utilize the ratio of annual runoff to annual precipitation as the transport process (Vadas, 2012a). The manure dissolved P component is the product of the runoff:rainfall ratio, the water extractable P (WEP) content of the manure, and a P distribution factor. The fertilizer dissolved P component is the product of the runoff:rainfall ratio, the P content of the fertilizer, and a different P distribution factor. The WEP content of the manure source is measured using a 250:1 water to solid ratio or can be converted from another WEP method. The manure P distribution factor is calculated as the runoff:rainfall ratio raised to the power of 0.225, while the fertilizer P distribution factor is calculated as 0.034 multiplied by the exponent of the runoff:rainfall ratio multiplied by 3.4. These unique distribution factors are meant to distribute the amount of P released from the amendment source between runoff and infiltration (Vadas, 2012a).

Phosphorus site indices are used across the country to determine the relative risk of P loss from agricultural fields to surface waters. As the indices move from management decision tools used by farmers to regulatory tools, PSIs must be updated to include the latest scientific research and evaluated for accuracy against P loss data. As indices are modified, it is important to understand how each component will affect the final PSI score and how sensitive the calculation is to the accuracy of the input data. This information can help inform users of the PSI how precise input data must be to obtain the most accurate PSI score. A full investigation of the effect of modifications to PSIs should be conducted before implementation of modified PSIs as regulatory tools to ensure ease of adoption by the public and accuracy of the resulting management recommendations.

The UM-PMT is slated to be implemented in 2014 to replace the use of the MD-PSI in nutrient management planning in Maryland. The current research is focused on evaluating the UM-PMT equation as a whole to understand potential ramifications of its implementation and to suggest future changes to improve its accuracy in predicting P loss risk. First, the UM-PMT equation was evaluated for accuracy by comparison of UM-PMT final scores calculated for both simulated and collected datasets to modeled P loss data, with modifications and new weighting factors suggested. From this evaluation, a new version of the UM-PMT was developed. The second objective was to determine how soil chemistry and hydrology in extensively ditched agricultural fields interacted to contribute to subsurface P loss. The third objective was to better understand DPS as a source factor for surface and subsurface dissolved P loss. Degree of P saturation represents a new input factor for the UM-PMT and can be calculated different ways. Finally, the MD-PSI, UM-PMT, and modified version of the UM-PMT were compared to one another with benefits and limitations of each index discussed. The objective was to understand how changes could potentially influence management changes across Maryland agriculture.

1.8 Tables

Table 1.1 Distribution of RUSLE scores into sediment risk transport factor (SED) values

RUSLE or RUSLE2† "A" Value	SED Value
<1	2
1 – 2	4
2 – 3	6
3 – 4	8
>4	10

Table 1.2. Surface runoff (SR) factor for Runoff component of University of Maryland Phosphorus Management Tool

	Soil Permeability Class (inches/hour)				
Slope (%)	Very Rapid (> 20)	Moderately Rapid *and* Rapid (2.0 to 20)	Moderately Slow *and* Moderate (0.2 to 2.0)	Slow (0.06 to 0.2)	Very Slow (< 0.06)
Concave	0.10	0.10	0.10	0.10	0.10
< 1	1.20	1.40	1.60	1.80	2.00
1 – 5	4.20	4.90	5.60	6.30	7.00
6 – 10	4.80	5.60	6.40	7.20	8.00
11 – 20	5.40	6.30	7.20	8.10	9.00
> 20	6.00	7.00	8.00	9.00	10.00

Table 1.3 Standard phosphorus source coefficients (PSC) for organic and inorganic amendments

Organic P Source	PSC
Default	0.6
Inorganic P fertilizer	0.6
Swine manure	0.6
Other manures (beef, dairy, poultry, horse, etc.)	0.5
BPR & BNR biosolids	0.5
Alum-treated manures	0.3
Biosolids (all except BPR & BNR biosolids)	0.2

Table 1.4 Phosphorus application method factor (AM_r) for RUNOFF component

Application Method	Value
None Applied	0
Subsurface placement or immediate full incorporation (>90% residue)	0.2
Incorporated within 5 days of application (≥50% residue)	0.4
Surface applied March - Nov. OR incorporated after 5 days OR <50% residue	0.6
Surface applied or incorporated after 5 days Dec. - Feb.	0.8

Table 1.5 Phosphorus application method factor (AM_{sub}) for SUBSURFACE component

Application Method	Value
None Applied	0
Incorporated within 5 days with soil mixing (precludes straight aerator) March - Nov.	0.32
Incorporated within 5 days with soil mixing (precludes straight aerator) Dec. - Feb.	0.4
Surface applied and subsurface placement without soil mixing (includes banded fertilizer and injection without soil mixing) March - Nov.	0.64
Surface applied and subsurface placement without soil mixing (includes banded fertilizer) Dec. - Feb.	0.8

Table 1.6. Subsurface drainage transport factor (SD) for the Subsurface component of the University of Maryland Phosphorus Management Tool

		Hydrologic Soil Group			
Soil Drainage Class	Risk Factor	A **1**	B **1.2**	C **1.2**	D **1**
Very Poorly Drained	**8**	8.0	6.7	6.7	8.0
Poorly Drained	**7**	7.0	5.8	5.8	7.0
Somewhat Poorly Drained	**6**	6.0	5.0	5.0	6.0
Moderately Well Drained	**5**	5.0	4.2	4.2	5.0
Well Drained	**6**	6.0	5.0	5.0	6.0
Somewhat Excessively Drained	**7**	7.0	5.8	5.8	7.0
Excessively Drained	**8**	8.0	6.7	6.7	8.0

Table 1.7 Interpretive categories for final score of University of Maryland Phosphorus Management Tool

P Loss Rating	Generalized Interpretation of P Loss Rating
0-50	**LOW** potential for P movement from this site given current management practices and site characteristics. Soil P levels and P loss potential may increase in the future due to continued nitrogen-based nutrient management. Total phosphorus applications should be limited to no more than a three-year crop P removal rate applied over a three year period.
51-100	**MEDIUM** potential for P movement from this site given current management practices and site characteristics. Practices should be implemented to reduce P losses by surface runoff, subsurface flow, and erosion. Phosphorus applications should be limited to the amount of P expected to be removed from the field by the crop harvest immediately following P application or soil-test based P application recommendations.
> 100	**HIGH** potential for P movement from this site given current management practices and site characteristics. No phosphorus should be applied to this site. Active remediation techniques should be implemented in an effort to reduce the P loss potential from this site.

Chapter 2. Use of Annual Phosphorus Loss Estimator (APLE) Model to Evaluate the University of Maryland Phosphorus Management Tool (UM-PMT)

2.1 Introduction

Phosphorus (P) and nitrogen (N) loss to surface water from point or non-point sources can contribute to eutrophication, which is a major water quality problem globally. Eutrophication refers to nutrient enrichment of surface water causing a surge of aquatic plant growth. This surge of growth can make aerobic habitats anaerobic when these plants die and decompose. Agriculture has been named as one of the primary non-point sources of excess nutrients leading to eutrophication (Sharpley et al., 2003). Eutrophication is an especially important issue in the state of Maryland, as the state surrounds the Chesapeake Bay. The Chesapeake Bay is a major estuary with a large watershed that encompasses six states and the District of Columbia. The Bay is especially at risk for eutrophication as the land draining into the Bay has areas of high agricultural production. One way of mitigating this issue was to develop comprehensive nutrient management plans on agricultural operations to record and manage the amount of nutrients applied to land as well as management practices used by farmers (Djodjic and Bergström, 2005; Sharpley et al., 2003).

Field extension agents, planners, and producers use the Phosphorus Site Index (PSI) to rank agricultural fields based on risk of P loss to surface water risk and then guide manure applications and management practices toward the lowest risk scenarios (Lemunyon and Gilbert, 1993; Sharpley et al., 2001). The PSI was designed as a simple, user-friendly tool requiring minimal data from the user, such as use of various management practices or timing of manure application (Djodjic and Bergström, 2005;

Gburek et al., 2000; Lemunyon and Gilbert, 1993). The Maryland Phosphorus Site Index (MD-PSI) has been a component of nutrient management planning in Maryland since its development in 2002 (Coale et al., 2002). Modifications to the MD-PSI have continued since then in an attempt to increase the ease of use and accuracy of the index.

In 2012, major modifications were made to the MD-PSI calculation, including a shift from a multiplicative model to a component model structure; and the resulting equation was renamed the University of Maryland Phosphorus Management Tool (UM-PMT). Collection of field-measured P loss data was necessary to evaluate the UM-PMT calculation for accuracy based on recommendations from the Southern Extension-Research Activity Group 17 (SERA-17). Sharpley et al. (2011) recommended evaluating PSIs against measured P loss data, however suggested that modeled P loss data could be used where measured data did not exist, if the model used to generate the data provided a reasonable estimate of P loss from the field (Sharpley et al., 2011).

Vadas et al. (2012) developed the Annual P Loss Estimator (APLE) model as a validated, field-scale P loss quantification model that runs on an annual time step (Vadas et al., 2012). The APLE model quantifies P loss through erosion and dissolved P (DP) lost through surface runoff but does not include any subsurface P loss pathways. The APLE model splits the erosion and DP pathways into sediment P, soil DP, manure DP, and fertilizer DP loss components (Vadas et al., 2012; Vadas et al., 2009). APLE integrates management practices, organic and inorganic P applications, and manure deposition from grazing animals in its P loss calculations. The APLE model is user friendly but requires additional input variables beyond a PSI, including annual precipitation, annual runoff, soil organic matter content, and clay percentage (Vadas, 2012a). The component nature of the APLE outputs as well as the user-friendly calculation of soil P dynamics made the APLE model appropriate for calculation of modeled P loss for the evaluation of the UM-PMT. The objectives of this study were to 1) compare the surface P loss components of the UM-PMT to modeled P loss data from APLE then 2) modify the UM-PMT to more precisely predict the relative risk of P loss.

2.2 Materials and Methods

2.2.1 Creation of Independent Datasets

Following the methods of Bolster et al. (2011), two independent datasets were used to evaluate the UM-PMT calculation. The first dataset was a large, simulated dataset created to calibrate the UM-PMT against P loading data, modeled using APLE, in order to suggest modifications and develop weighting coefficients for the components of the UM-PMT. The second dataset, a field dataset, was compiled by using site information collected from farms across Maryland, and was used to evaluate UM-PMT equation compared to modeled P losses calculated using APLE. During this process, the UM-PMT was modified iteratively to improve the relationship between its output and APLE output.

The field dataset was collected from 382 agricultural fields across the state of Maryland (Table 2.1) visited between 2011 and 2012. Soil samples were collected (0 to 20 cm depth) from each field, oven dried and ground to pass through a 2 mm sieve. For each soil sample, P, Fe, and Al concentrations were measured using Mehlich 3 extraction (1:10 soil/0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.015M NH_4F + 0.13M HNO_3 + 0.0001M EDTA, (Mehlich, 1984)) and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Researchers documented physical site characteristics and management practices required to calculate the UM-PMT during each field visit. Field slope was measured using clinometers and distance to surface water was measured in field with a laser rangefinder if surface water was easily seen. If water was not visible, a soil survey or aerial imagery in Geographic Information System (GIS) software was used to determine distance to water.

The UM-PMT was designed for use on fields with soil P concentrations greater than 150 FIV where the producer plans to apply a P amendment. The final score of the UM-PMT indicates the relative risk of P loss from a field, with management recommendations given for fields with high risk of P loss. Some fields sampled had soil P concentrations resulting in a FIV less than 150 or no P application planned. In these situations, a soil P concentration of 150 FIV was substituted and manure application was simulated.

To simulate manure application, a field was first assigned an organic P type, (i.e. beef, dairy, poultry, or biosolids), then manure total solids content, water extractable P (WEP) concentration, and proportion of the total P that was water extractable (WEP %) was assigned from a predefined range for each organic P type using a uniform distribution. The ranges for the variables were obtained from the literature (Kleinman et al., 2005) and manures with >15% solids were treated as solid manures with the remaining manures treated as liquid. The ranges from the literature for WEP and WEP% for each manure type were large and there was little differentiation between manure types. Therefore the range was calculated plus or minus one standard deviation of the mean values reported in the literature. The total P concentration in manure was calculated by dividing WEP concentration by WEP%. A P application rate was assigned using a random, uniform distribution constrained based on reasonable P_2O_5 application rates used in Maryland, 0 to 400 lbs P_2O_5 ac^{-1}. The manure application rate was then calculated as the P_2O_5 application rate divided by manure TP concentration.

A simulated dataset was created to evaluate iterations of the UM-PMT after modifications and to create weighting coefficients. The simulated dataset was created to represent the possible combinations of physical and management conditions that could exist in Maryland agricultural fields. The dataset was created using SAS 9.3 (SAS Institute, 2009) and consisted of 15000 fields, with variables necessary to calculate APLE, MD-PSI, and UM-PMT included for each field. Values for the variables were randomly assigned using a uniform distribution of values within a predefined range. The uniform distribution ensured each value within the range would be present an equal number of times throughout the dataset. The range for each variable was defined using literature values or the field dataset previously described.

The simulated dataset was created by first assigning independent variables and then deriving dependent variables from these. First, each field was first assigned to a Maryland county and then the corresponding physiographic region. The rainfall-runoff erosivity (R) factor used in RUSLE and crop rotation was assigned based on county. Crop rotation was included for calculation of the RUSLE cover-management (C) factor and we assigned by county, as some rotations more specific to individual farming operations (i.e. silage used on dairy operations) would only be found in certain counties within Maryland. In order to simplify the simulation, the current crop was assumed to be corn as this would be the most common crop out of any rotation where manure or other organic P source would be applied. Tillage for the corn crop was randomly assigned using a uniform distribution, while the tillage for the previous crop was randomly assigned, except for a continuous corn rotation, where no previous tillage operation was required for calculation of the C factor. The RUSLE support practice (P) factor defaulted to one, unless artificial drainage was present in a field, where the P factor score was 0.6. Annual precipitation in inches was calculated for each county from daily precipitation data collected for 2011 at USGS gauging located in each county, downloaded from USGS Water Data website (waterdata.usgs.gov). One year's worth of precipitation data was used because some gauging stations did not have more than one year's worth of daily precipitation data available. Additionally, an average of daily precipitation over a number of years resulted in the loss of the large storm events that took place in the individual years. Annual runoff that was calculated using average daily precipitation values was much less than annual runoff calculated using one year's worth of precipitation data.

All fields were assumed to have an organic nutrient application for the corn crop, so each field was assigned either biosolids, beef, dairy, poultry, or swine manure and manure application was simulated as previously described for the field dataset. Each field was assigned one method of manure application based on the categories found in the guidance document for the UM-PMT (McGrath et al., 2013). If the field was assigned no-till as the tillage method for the corn crop, then the manure application method defaulted to surface application. The remaining fields were assigned to the other application methods by uniform distribution, but only liquid manures were eligible for injection.

Soil Survey Geographic Database (SSURGO) data was downloaded for each Maryland county and assigned to fields by county with a uniform distribution, ensuring each soil type was represented equally within the dataset. Soil types were removed that would not be used for agriculture, including soil types with slope greater than 15% or with a land capability class V, VI, or VII. Additional soil types were removed if they did not have the complete set of properties required to calculate any of the equations used in APLE, MD-PSI, or UM-PMT. Variables obtained from the soils data include depth to mean high water table, drainage class, hydrologic soil group (HSG), land capability class, minimum and maximum slope, sand, silt, clay, and organic matter content, saturated hydraulic conductivity, and a RUSLE soil erodibility (K) factor.

Concentrations of Mehlich 3-extractable P (M3P) and presence of a no P application zone were assigned to fields using a uniform distribution with maximum and minimum values determined statewide from the collected dataset. For some variables, a uniform, statewide distribution of values was not appropriate, and it was more appropriate to assign variable based on the proportion of the county or region where variable characteristics were observed in the collected dataset. For example, only some fields on Maryland's eastern shore contain artificial drainage. In order to simulate this, the percentage of fields from the collected dataset that contained artificial drainage was determined for each Eastern Shore region and the presence of artificial drainage was assigned to fields in the simulated dataset ensuring the same percentage of fields had artificial drainage in each Eastern Shore region. This same analysis and variable assignment was performed by region for condition of buffers, width of buffer, presence of artificial drainage, and distance to surface water and was performed by county for slope length and priority of receiving water body.

Annual runoff was calculated for both the simulated and collected datasets by using the SCS Curve Number method (USDA-SCS, 1972) and the one-year daily precipitation data for each county. This method requires HSG and surface condition to determine the curve number variable, then runoff is calculated on a daily time-step using daily precipitation data and curve number, then summed for the year to result in annual runoff. If the tillage practice for the corn crop was no-till, the field was assigned a "good" surface condition with the remaining fields assigned "poor" condition and curve number variable for that field was assigned based on condition and HSG. Runoff in inches was calculated for each day for each possible curve number for each county, then assigned to each field based on county and curve number. Sediment loss was calculated using RUSLE (Equation 1.2).

Degree of P saturation (DPS) has historically been determined as the molar ratio of ammonium oxalate extractable soil P to the sum of Al and Fe concentrations, with a coefficient in the denominator which adjusts the total Fe and Al available for P sorption. Recently, soil testing laboratories have begun reporting an estimated DPS based on Mehlich 3 extractable P, Fe, and Al. For the collected dataset, P saturation ratio (M3PSR-I) was first calculated (Equation 1.7) then converted to Mehlich 3 degree of P saturation (DPS_{M3}) through linear conversion (Equation 1.) based the method of Sims et al. (2002). For the simulated dataset, it was determined the random assignment of soil P, Al, and Fe concentrations would produce unreasonable values for DPS, therefore a linear relationship between DPS and M3P was obtained from the literature [DPS=(0.18*M3P)+12.2, (Sims et al., 2002)]. Since DPS is likely related to M3P, DPS was assigned to fields based on M3P concentration using the linear conversion. For all fields in both the collected and simulated datasets, MD PSI, UM-PMT, and APLE were calculated following guidance documents (Coale, 2008; McGrath et al., 2013; Vadas, 2012b).

The simulation created a dataset with 15000 simulated fields; but for the comparison between UM-PMT and APLE, fields with RUSLE score greater than 8 ton ac^{-1} or DPS values greater than 120% were eliminated from the dataset. This was done because while the individual variables fell within defined ranges that were possible, the combinations that resulted in extreme values for RUSLE or DPS would be unlikely to occur in Maryland conditions. From a programming standpoint, unrealistic combinations resulting in derived values outside of common ranges were excluded rather than include complex logic statements that prohibited these unrealistic combinations. Even after elimination of unrealistic values the final, simulated dataset was large enough to accomplish research objectives.

2.2.2 Algebraic Distribution of UM-PMT Equation

To allow for comparison between the outputs of APLE and UM-PMT, the UM-PMT equation was modified and distributed algebraically to calculate the same P loss outputs as the APLE model (Figure 2.1). Since APLE only estimates surface P loss, the SUBSURFACE component of the UM-PMT was removed. The 0.1 weighting factor was removed, as new weighting coefficients would be calculated. The distance buffer factor (DBF) was also removed, as it modifies the UM-PMT score based on a field's distance to surface water, and it is not applicable in the comparison to APLE, an edge-of-field model.

The RUNOFF component of the UM-PMT combines risk of surface dissolved P (DP) loss from both soil and manure, therefore the RUNOFF component was distributed to separate the two P loss pathways (Figure 2.1). The dissolved P risk factor (DPR_r) in the UM-PMT RUNOFF component represents the combined source and management risk index for dissolved P loss in surface runoff. The SOILDP source factor was calculated as two times the DPS, however the scaling factor of 2 was removed since the evaluation process would provide more precise scaling factors. The manure DP source risk factor for the RUNOFF component, identified as WSP_r, was calculated by multiplying the TP applied by the P source coefficient (PSC). The PSC represents the proportion of P in the applied P that is water-extractable (Elliott et al., 2006). A nutrient management planner can select a PSC from a lookup table (Table 1.3) or calculate the PSC as 0.117*WEP content of manure, determined from analysis using a 1:200 solid/solution ratio (Wolf et al., 2005). For the purposes of this study, the PSC was calculated using the WEP that was generated for each simulated manure application.

The WSP_r was calculated as a sum of all P applications to be made in the current planning period. The WSP_r was then modified by the application management risk factor (AM_r), which represents the relative risk of management practices for timing, method of application, and incorporation of the P source. Included in the APLE model are two variables representing percentage of manure incorporated into the soil as well as depth of incorporation. The only similar variable within the UM-PMT, the AM_r factor, is categorical and decreases MANURE DP value based on implementation of desirable management practices that incorporate manure into the soil after application. Although this variable is categorical, it was retained for the evaluation to represent manure incorporation. The distributed output for the UM-PMT and the APLE model are shown in Figure 2.1.

2.2.3 Output Comparison

Linear regression using PROC REG (SAS Institute, 2009) was performed on each corresponding UM-PMT and APLE component (Table 2.2). Multiple iterations of modifications were made to the UM-PMT calculation, with linear regression performed after each modification to compare model outputs. Following modifications, weighting coefficients were calculated for each of the model outputs using the simulated dataset using Equation 2.1 (Bolster et al., 2011), by determining the exponent of the mean weighted difference between APLE and UM-PMT values for each component.

Equation 2.1 Minimized difference between University of Maryland Phosphorus Management Tool (UM-PMT) and Annual Phosphorus Loss Estimator (APLE) outputs to determine weighting coefficients (W) for each component of the University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2)

$$W = e^{\Sigma(\frac{log\,APLE - log\,UM-PMT}{n})}$$

Therefore, Equation 2.1 was calculated for PARTICULATE, SOIL DP, and MANURE DP components resulting in three unique weighting values. Each weighting coefficient was included in the modified version of the UM-PMT, resulting in the University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2). Final score for the UM-PMT v.2 was calculated for all fields in the simulated dataset then compared to corresponding APLE output. Finally, to verify results, UM-PMT, UM-PMT v.2, and APLE outputs were calculated for all fields in the collected dataset and linear regression was performed between APLE outputs and corresponding outputs from both UM-PMT and UM-PMT v.2.

2.3 Results and Discussion

In the initial comparison between UM-PMT and APLE, the relationship between SOIL and MANURE DP components was weak, with R^2 of 0.01*** and 0.26*** observed for MANURE DP and SOIL DP, respectively (Table 2.3). The R^2 values for PARTICULATE P and TOTAL P were much stronger (R^2=0.66*** and 0.61***, respectively), but visual inspection of the regression plots showed despite a high R^2 value, the PARTICULATE P relationship appeared to have a stepwise pattern (Figure

2.2a). This was attributed to the categorical nature of the SED variable in the UM-PMT. Since particulate-bound P loss is responsible for the largest proportion of P loss from fields, it is likely the strong R^2 value for TOTAL P was a result of the strong R^2 for PARTICULATE P.

In the regression plot for SOIL DP (Figure 2.3a), there was a wide range of APLE values for one UM-PMT component value, meaning the UM-PMT equation was lacking precision. The MANURE DP regression plot (Figure 2.4a) also showed poor precision, as there are fields with a wide range of P loss predicted from APLE that scored similarly within the UM-PMT and a wide range of UM-PMT scores calculated for the same P loss predicted by APLE. The initial UM-PMT equation exhibited a lack of precision in ranking fields according to their modeled P loss, indicating a need to modify the UM-PMT to increase precision.

The UM-PMT was modified iteratively multiple times in order to achieve the strongest correlation between UM-PMT and APLE outputs. The components of UM-PMT, APLE, and UM-PMT v.2 are presented in Table 2.2 and the final equation for UM-PMT v.2 is presented in Equation 2.2. Within Equation 2.2, RUSLE is the revised universal soil loss equation (Renard et al., 1997), FIV is Maryland P fertility index value representing soil P concentration, DF is the distance factor, BF is the buffer factor, runoff is annual runoff in inches, DPS is degree of P saturation as a percent, SM is soil management factor, Timing represents timing of amendment application, rainfall is annual precipitation in inches, WEP% is percentage of manure that is water extractable, $AM_{r\text{-}v.2}$ and AM_{sub} are application method for runoff and subsurface components, respectively, SD is subsurface drainage transport factor, and AM is amendment management factor.

Equation 2.2 University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2)

$$\text{UMPMT v.2} = \text{Particulate} + \text{SoilDP} + \text{ManureDP} + \text{FertilizerDP} + \text{Subsurface}$$

Where

$$\textbf{Particulate} = 0.115 * \text{RUSLE} * \text{FIV} * \text{DF} * \text{BF}$$

$$\textbf{SoilDP} = 0.713 * (\text{Runoff} * 10^{-6}) * (0.0259 * \text{DPS}) * \text{DF} * \text{BF} * \text{SM} * \text{Timing}$$

$$\textbf{ManureDP} = 1.12 * (\text{Runoff/Rainfall})^{1.25} * [(\text{manure kg } P_2O_5/\text{ha}) * \text{WEP\%} * \text{AM}_{\text{r-V.2}}] * \text{DF} * \text{BF} * \text{AM} * \text{Timing}$$

$$\textbf{FertilizerDP} = [0.34 * e^{3.4 * (\text{Runoff/Rainfall})} * (\text{Runoff/Rainfall})] * [(\text{fertilizer kg } P_2O_5/\text{ha}) * \text{AM}_{\text{r-V.2}})] * \text{DF} * \text{BF} * \text{AM} * \text{Timing}$$

$$\textbf{Subsurface} = \text{SD} * \text{DPS} * \text{AM}_{\text{sub}} * \text{AM}$$

The APLE model contained only continuous variables since, in fact, most factors in the real-world controlling P loss are continuous in nature. Therefore, it was hypothesized that simply modifying the UM-PMT to include only continuous variables where possible would increase output correlation. The surface runoff (SR) variable in the MANURE DP component and sediment factor (SED) in the PARTICULATE P component are both categorical variables and were replaced with the runoff-rainfall ratio from APLE and numerical RUSLE score, respectively, in the UM-PMT v.2 (Table 2.2).

The source factor of the SOIL DP component remained as DPS, however the weighting factor of 2 was replaced with 0.0259, to convert DPS to units of mg-P L^{-1} (Vadas et al., 2005). The SR factor in the SOIL DP component was replaced with annual runoff in kg ha^{-1}, as this was the transport factor for soil DP loss in APLE (Vadas, 2012a). Modifications to the source factor for the MANURE DP component included the use of the quantity of P_2O_5 (in kg ha^{-1}) applied to a field multiplied WEP%, which can either be measured by performing a manure analysis as previously described or calculated from the PSC for the manure type, using the equation WEP% = PSC/0.117 (Elliott et al., 2006). The manure source was then multiplied by AM_r, which did not change from the original UM-PMT calculation. This was the only factor that remained in the equation that was categorical, as manure application methods were ranked based on how well the practice reduced risk of P loss through that pathway.

Modifications were also made to the FERTILIZER DP and SUBSURFACE components, though they were not considered in this evaluation. The FERTILIZER DP component was not evaluated in this study as there were no fields in the collected dataset that were applying inorganic P amendments. The FERTILIZER DP component was modified similar to the MANURE DP component: the same transport pathways used in APLE for risk of fertilizer DP loss were incorporated into UM-PMT v.2 and the source factor assumed the same template as MANURE DP, with the elimination of PSC, as the entirety of inorganic P amendments are available for environmental loss. No weighting coefficient was calculated for this component.

The APLE model does not include a subsurface P loss output, so the SUBSURFACE component of the UM-PMT could not be evaluated. However, if a quantitative model such as APLE that includes subsurface P transport becomes available, it would be prudent to perform a similar evaluation as was performed for the surface P loss components. Nonetheless, some adjustments were made to the SUBSURFACE component based on the current state of the science of subsurface P transport. The SUBSURFACE source factor was modified to only include soil DPS, but the transport factor remained the same. The final calculation of UM-PMT v.2 was adjusted so that when artificial drainage (such as a tile drain or a ditch) was present, only the SUBSURFACE component is calculated and represents the entire UM-PMT v.2 final score. Final scores for both versions of the UM-PMT equation were compared for fields within the collected dataset where artificial drainage was present and a similar distribution among interpretive categories was observed (Table 2.5).

Other variables that were modified or included in the UM-PMT v.2 equation but not considered in the evaluation are distance factor (DF), buffer factor (BF), soil management factor (SM), timing factor, and amendment management factor (AM). The SM factor reduces SOIL DP score if P-sorbing materials are incorporated into the soil, the timing factor reduces MANURE DP score if manure is applied in the spring, and the AM factor reduces MANURE DP or SUBSURFACE score if beneficial management practices are utilized in the field.

The modifications to the UM-PMT increased the R^2 appreciably for the regression between the UM-PMT and APLE outputs for all model components for the simulated dataset (Table 2.3), with a 60-fold increase in R^2 for MANURE DP (R^2=0.01 to 0.59). Visual inspection of the regression plots for the modified UM-PMT equation showed more linear patterns for each output (Figure 2.2b-2.4b). Discrete linear relationships were observed in the MANURE DP plot (Figure 2.4b), due to the categorical nature of the AM_r variable present in the UM-PMT equation. The inclusion of weighting coefficients within the UM-PMT v.2 calculation slightly increased R^2 values for the TOTAL P (Table 2.3) comparison but more notably modified range of calculated values for the UM-PMT (Figure 2.2-2.4c), and this was most apparent for the PARTICULATE P component (Figure 2.2c).

Component and final scores for each field in the collected dataset were calculated using the original UM-PMT and UM-PMT v.2. The modifications to the UM-PMT and the inclusion of the weighting coefficients increased the R^2 values for each component

(Table 2.4). The R^2 value for MANURE DP with the original UM-PMT were higher for the collected dataset than the simulated dataset and this is likely due to the portion of the dataset with manure application data that was collected as opposed to simulated. Visual inspection of regression plots (Figure 2.5) illustrated a stronger linear relationship in addition to the increased R^2 values between UM-PMT v.2 and APLE.

Fields with a final score for both version of the UM-PMT less than 50 are categorized as low risk for P loss (LOW), while fields with final score 51-100 are categorized a medium risk for P loss (MEDIUM), and fields with final score >100 are categorized as high risk for P loss (HIGH). Final scores for both version of the UM-PMT were compared for all fields in the collected dataset. Almost half of the fields in the collected dataset (44%) were categorized as HIGH and 23% of fields were categorized as LOW with both versions of the UM-PMT equation. For 32% of fields in the collected dataset, the UM-PMT equation categorized these fields as HIGH and the UM-PMT v.2 categorized these fields as LOW (Figure 2.6).

2.4 Conclusions

A strong, linear relationship was not present between the original UM-PMT equation and modeled P loss data predicted by APLE for the simulated dataset. Modifications to the UM-PMT calculation, including replacement of categorical variables with continuous variables and the use of variables more similar to APLE, increased correlation between UM-PMT and modeled P loss data for the simulated dataset. Unique weighting coefficients for each P loss component were calculated and increased correlation of UM-PMT v.2 final score and modeled P loss. Additionally, the UM-PMT equation categorized a greater proportion of field as high risk for P loss than the UM-PMT v.2 equation. Due to the improved precision of the prediction of relative risk of P loss, it is recommended that the UM-PMT v.2 be adopted as the Maryland P Index equation.

2.5 Tables

Table 2.1 Number of fields sampled in each county in Maryland in the collected dataset

County	Number of fields	Percentage of Total Dataset	Region
Allegany	10	2.6	Ridge and Valley
Anne Arundel	12	3.1	Coastal Plains – Western Shore Uplands
Baltimore	9	2.4	Piedmont
Calvert	33	8.6	Coastal Plains – Western Shore Uplands
Caroline	25	6.5	Coastal Plains – Delmarva Peninsula
Carroll	11	2.9	Piedmont
Cecil	17	4.4	Piedmont
Charles	8	2.4	Coastal Plains – Western Shore Uplands
Dorchester	15	3.9	Coastal Plains – Delmarva Peninsula
Frederick	6	1.6	Blue Ridge
Garrett	23	6.0	Appalachian Plateaus
Harford	9	2.4	Piedmont
Howard	10	2.6	Piedmont
Kent	9	2.4	Coastal Plains – Delmarva Peninsula
Montgomery	4	1.1	Piedmont
Prince George’s	10	2.6	Coastal Plains – Western Shore Uplands
Saint Mary’s	24	6.3	Coastal Plains – Western Shore Uplands
Somerset	55	14.4	Coastal Plains – Delmarva Peninsula
Talbot	21	5.5	Coastal Plains – Delmarva Peninsula
Washington	22	5.8	Ridge and Valley
Wicomico	17	4.4	Coastal Plains – Delmarva Peninsula
Worcester	17	4.4	Coastal Plains – Delmarva Peninsula

Table 2.2 Outputs of Annual Phosphorus Loss Estimator (APLE) model with the corresponding outputs of the University of Maryland Phosphorus Management Tool (UM-PMT),and University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2) used for the output comparison.

	UM-PMT		APLE		UM-PMT Version 2		
Output	**Source**	**Transport**	**Source**	**Transport**	**Weighting Coefficient**	**Source**	**Transport**
Manure DP	Total P * PSC * Application method (AM_r)	Slope * Permeability	Manure P_2O_5 * %WEP * Incorporation	$(\text{Runoff/Rainfall})^{1.25}$	1.05	Manure P_2O_5 * %WEP * Application Method ($AM_{r\text{-}v.2}$)	$(\text{Runoff/Rainfall})^{1.25}$
Soil DP	DPS	Slope * Permeability	(Mehlich 3-P * 0.5) * 0.005	Runoff (L/ha) * (10^{-6})	0.670	DPS*0.0259	Runoff (L/ha) * (10^{-6})
Sediment P	Mehlich 3-P FIV	RUSLE - category	Soil TP	RUSLE * Erosion Ratio	0.155	Mehlich 3-P FIV	RUSLE score

* represents multiplication

Total P = total P_2O_5 applied in lbs-P_2O_5 ac^{-1}; DPS = degree of phosphorus saturation; PSC = phosphorus source coefficient; FIV = fertility index value; Permeability = soil permeability class; soil TP = total P content of soil in mg kg^{-1}; runoff = annual runoff in mm; rainfall = annual rainfall in mm; RUSLE = annual sediment loss in tons ac^{-1}; WEP = water extractable P of manure

Table 2.3 Correlation coefficient (R^2) values for the comparison between iterations of the University of Maryland Phosphorus Management Tool (UM-PMT) and the outputs of the Annual Phosphorus Loss Estimator (APLE) model for the simulated dataset (n=8644)

	Component			
	Particulate P	**Manure DP**	**Soil DP**	**Total P**
Model Iteration	**R^2**			
UM-PMT	0.70	0.01	0.37	0.62
Modified UM-PMT†	0.84	0.58	0.99	0.73
UM-PMT v.2‡	0.84	0.58	0.99	0.75

All R^2 $P<0.0001$, RUSLE >8 ton ac^{-1} and DPS >120% removed from dataset

†UM-PMT equation with modifications without weighting coefficients

‡Equation includes weighting coefficients

Table 2.4 Correlation coefficient (R^2) values for the comparison between iterations of the University of Maryland Phosphorus Management Tool (UM-PMT) and the outputs of the Annual Phosphorus Loss Estimator (APLE) model for the collected field dataset (n=382)

	Component			
	Particulate P	**Manure DP**	**Soil DP**	**Total P**
Model Iteration	**R^2**			
UM-PMT	0.1	0.31	0.04	0.09
UM-PMT v.2	0.97	0.64	0.63	0.97

Table 2.5 Distribution of fields with artificial drainage present from the collected dataset into interpretive categories for UM-PMT and UM-PMT v.2 (n=121)

Interpretive Category	**UM-PMT†**	**UM-PMT v.2‡**
Low	1	5
Medium	3	14
High	117	102

†Final score for fields with artificial drainage was calculated as the sum of subsurface and surface P loss components.

‡Final score for fields with artificial drainage was calculated at UM-PMT Subsurface component only. Management factor (AM_{sub}) was not included for this evaluation.

2.6 Figures

a.

$$UMPMT = (SUBSURFACE + RUNOFF + PARTICULATE)$$

$$\text{Where}$$

$$SUBSURFACE = 0.1 * SD * DPR_{sub}$$

$$RUNOFF = 0.1 * DBF * SR * DPR_{r}$$

$$PARTICULATE = 0.1 * DBF * SED * FIV$$

b.

$$RUNOFF = DBF * 0.1 * SR * DPR_{r}$$

$$PARTICULATE = DBF * 0.1 * SED * FIV$$

c.

$$RUNOFF = SR * DPR_{r}$$

$$PARTICULATE = SED * FIV$$

d.

$$DPR_{r} = WSP_{r} + (2 * DPS)$$

$$\sum_{0}^{n} WSP_{r} = \sum_{0}^{n} OrgP * AM_{r}$$

$$OrgP = PSC * TP$$

$$RUNOFF = SR * [(OrgP * AMr) + (2 * DPS)]$$

e.

$$ManureDP = SR * OrgP * AM_{r}$$

$$SoilDP = SR * DPS$$

$$SedimentP = SED * FIV$$

Figure 2.1 Algebraic distribution of the RUNOFF and PARTICULATE components of the University of Maryland Phosphorus Management Tool (UM-PMT) to correspond with the Manure DP, Soil DP, and Sediment P outputs for the Annual Phosphorus Loss Estimator (APLE) model for calculation of outputs for comparison.

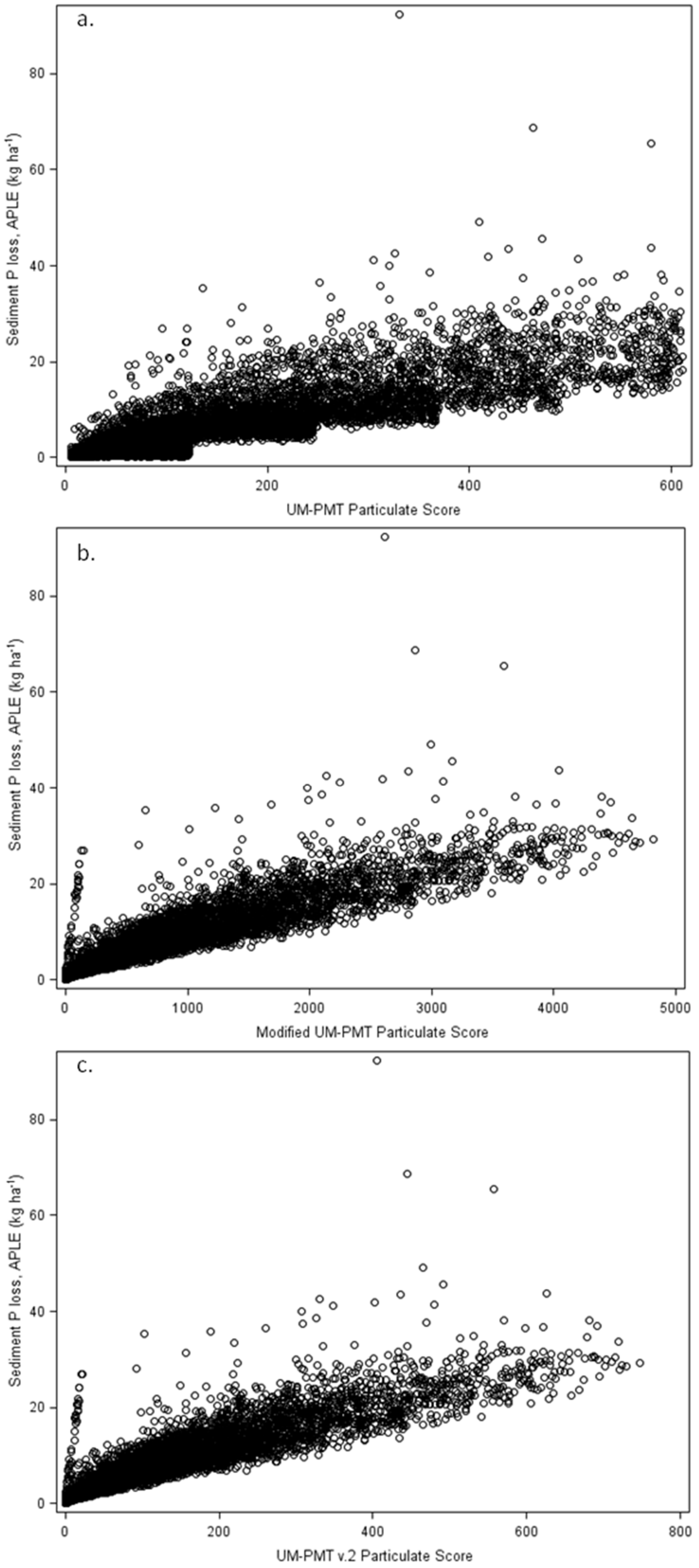
a.
Sediment P loss, APLE (kg ha^{-1})
0
20
40
60
80
0
200
400
600
UM-PMT Particulate Score
b.
Sediment P loss, APLE (kg ha^{-1})
0
20
40
60
80
0
1000
2000
3000
4000
5000
Modified UM-PMT Particulate Score
c.
Sediment P loss, APLE (kg ha^{-1})
0
20
40
60
80
0
200
400
600
800
UM-PMT v.2 Particulate Score

Figure 2.2 Modeled sediment P loss in kg ha^{-1} as estimated by the Annual Phosphorus Loss Estimator (APLE) model versus (a) the PARTICULATE component of the University of Maryland Phosphorus Management Tool (UM-PMT), (b) the PARTICULATE component of the modified version of the UM-PMT without a weighting coefficient, and (c) the PARTICULATE component of the UM-PMT version 2 (UM-PMT v.2) for the simulated dataset (n=10249). The unique weighting coefficients included in UM-PMT v.2 modified the scale of the X axis from (b) to (c).

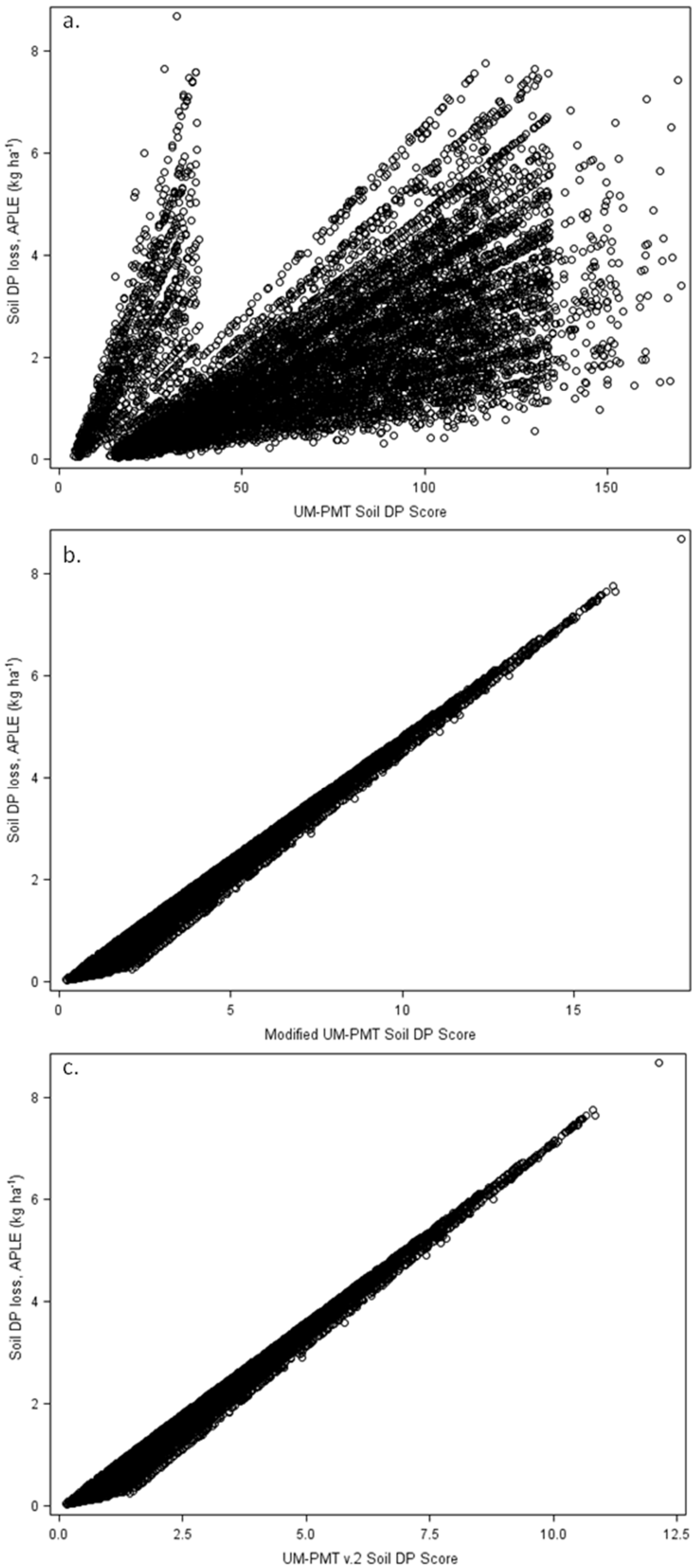
a.
Soil DP loss, APLE (kg ha^{-1})
0
2
4
6
8
0
50
100
150
UM-PMT Soil DP Score
b.
Soil DP loss, APLE (kg ha^{-1})
0
2
4
6
8
0
5
10
15
Modified UM-PMT Soil DP Score
c.
Soil DP loss, APLE (kg ha^{-1})
0
2
4
6
8
0.0
2.5
5.0
7.5
10.0
12.5
UM-PMT v.2 Soil DP Score

Figure 2.3 Modeled soil dissolved P (DP) loss in kg ha^{-1} as estimated by the Annual Phosphorus Loss Estimator (APLE) model versus (a) the SOIL DP component of the University of Maryland Phosphorus Management Tool (UM-PMT), (b) the SOIL DP component of the modified version of the UM-PMT without a weighting coefficient, and (c) the SOIL DP component of the UM-PMT version 2 (UM-PMT v.2) for the simulated dataset (n=10249). The unique weighting coefficients included in UM-PMT v.2 modified the scale of the X axis from (b) to (c).

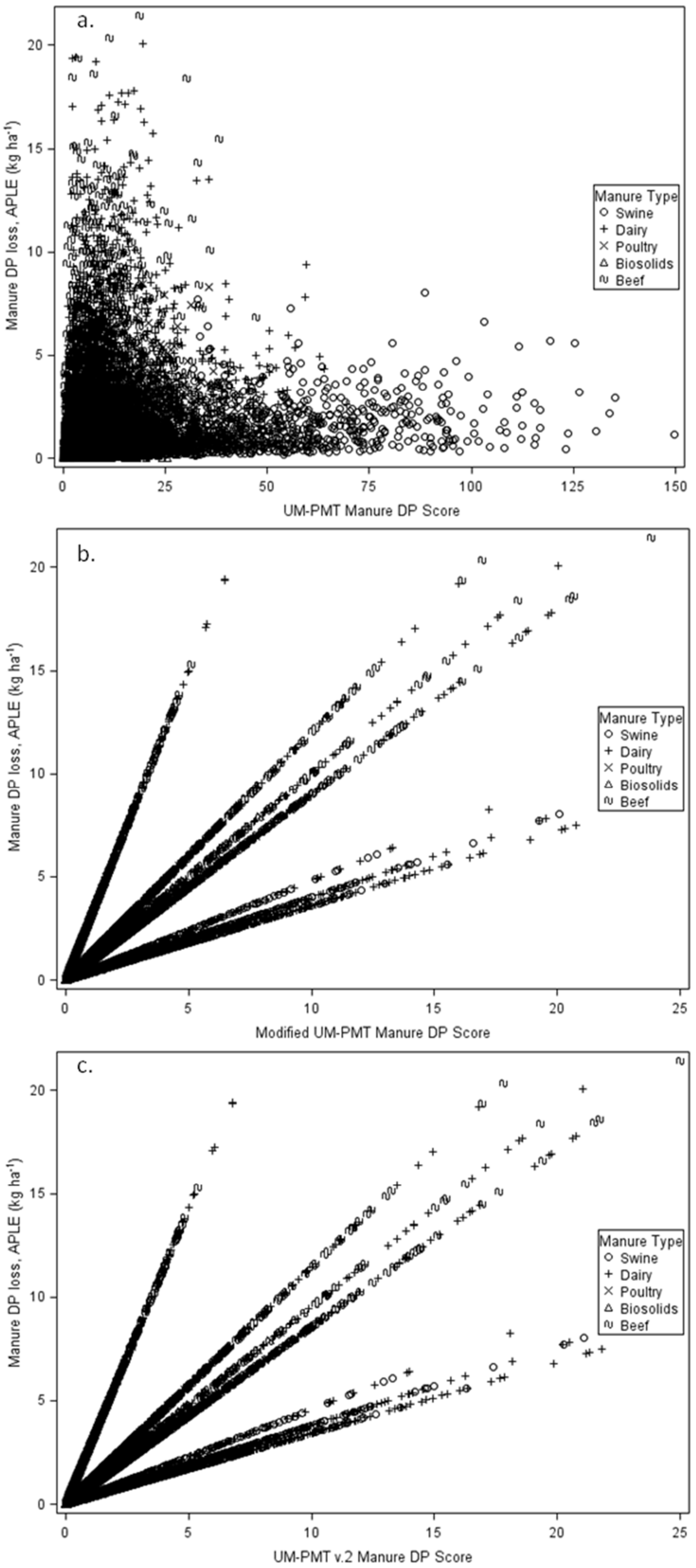
a.
Manure DP loss, APLE (kg ha-1)
UM-PMT Manure DP Score
0
25
50
75
100
125
150
0
5
10
15
20
Manure Type
Swine
Dairy
Poultry
Biosolids
Beef
b.
Manure DP loss, APLE (kg ha-1)
Modified UM-PMT Manure DP Score
0
5
10
15
20
25
Manure Type
Swine
Dairy
Poultry
Biosolids
Beef
c.
Manure DP loss, APLE (kg ha-1)
UM-PMT v.2 Manure DP Score
0
5
10
15
20
25
Manure Type
Swine
Dairy
Poultry
Biosolids
Beef

Figure 2.4 Modeled manure dissolved P (DP) loss in kg ha^{-1} as estimated by the Annual Phosphorus Loss Estimator (APLE) model versus (a) the MANURE DP component of the University of Maryland Phosphorus Management Tool (UM-PMT) by manure type, (b) the MANURE DP component of the modified version of the UM-PMT without a weighting coefficient by manure type, and (c) the MANURE DP component of the UM-PMT version 2 (UM-PMT v.2) by manure type for the simulated dataset (n=10249). The unique weighting coefficients included in UM-PMT v.2 modified the scale of the X axis from (b) to (c).

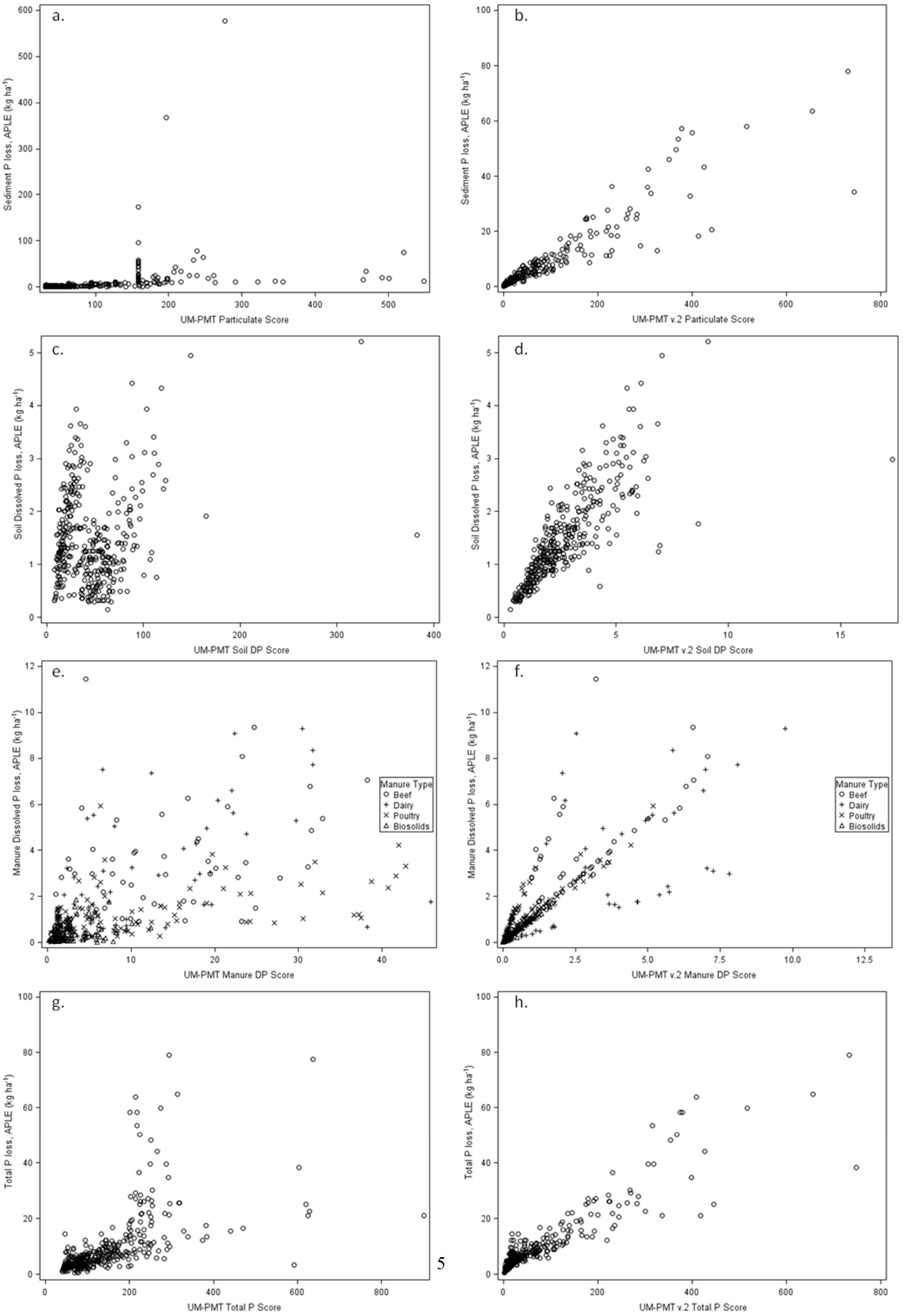
a.
Sediment P loss, APLE (kg ha^{-1})
UM-PMT Particulate Score
0
100
200
300
400
500
600
b.
Sediment P loss, APLE (kg ha^{-1})
UM-PMT v.2 Particulate Score
0
20
40
60
80
100
200
400
600
800
c.
Soil Dissolved P loss, APLE (kg ha^{-1})
UM-PMT Soil DP Score
0
1
2
3
4
5
100
200
300
400
d.
Soil Dissolved P loss, APLE (kg ha^{-1})
UM-PMT v.2 Soil DP Score
0
5
10
15
e.
Manure Dissolved P loss, APLE (kg ha^{-1})
UM-PMT Manure DP Score
Manure Type
Beef
Dairy
Poultry
Biosolids
0
2
4
6
8
10
12
20
30
40
f.
Manure Dissolved P loss, APLE (kg ha^{-1})
UM-PMT v.2 Manure DP Score
Manure Type
Beef
Dairy
Poultry
Biosolids
0.0
2.5
5.0
7.5
10.0
12.5
g.
Total P loss, APLE (kg ha^{-1})
UM-PMT Total P Score
0
20
40
60
80
100
200
400
600
800
h.
Total P loss, APLE (kg ha^{-1})
UM-PMT v.2 Total P Score
0
20
40
60
80
100
200
400
600
800

Figure 2.5 Modeled P loss in kg ha-1 as estimated by the Annual Phosphorus Loss Estimator (APLE) model versus components of the University of Maryland Phosphorus Management Tool (UM-PMT) for the collected dataset (n=382). Particulate P loss versus (a) UM-PMT and (b) UM-PMT v.2 PARTICULATE components, soil dissolved P (DP) loss versus (c) UM-PMT and (d) UM-PMT v.2 SOIL DP components, manure DP loss versus (e) UM-PMT and (f) UM-PMT v.2 MANURE DP components, and total P loss versus

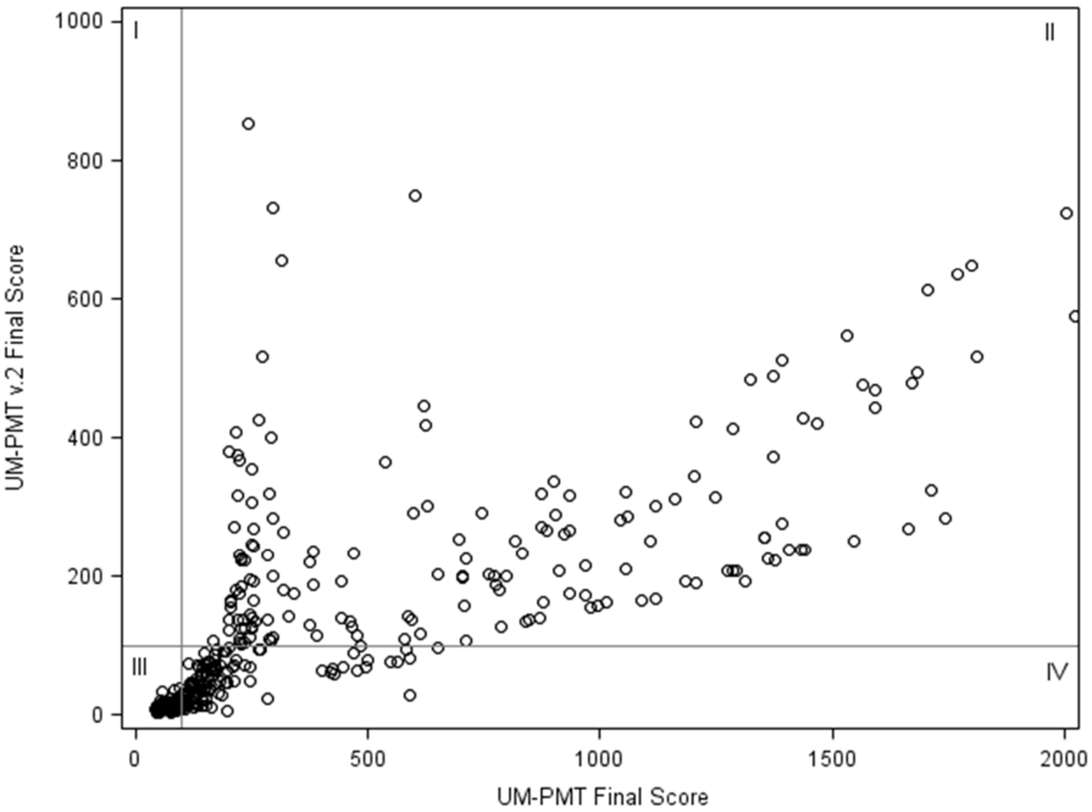

Figure 2.6 Final score for University of Maryland Phosphorus Management Tool (UM-PMT) versus final score for UM-PMT Version 2 (UM-PMT v.2) for the collected dataset (n=382). UM-PMT versus UM-PMT v.2 final scores for collected dataset. Final score greater than 100 indicated high risk of P loss and no P amendment application is recommended. Quadrant II indicates fields identified as having high risk of P loss using both equations while Quadrant IV indicates fields identified as high risk for P loss using UM-PMT equation only.

Chapter 3. Investigation of deep soil characteristics at artificially drained agricultural fields on the Delmarva Peninsula

3.1 Introduction

The University of Maryland Phosphorus Management Tool (UM-PMT) is an updated version of the Maryland Phosphorus Site Index (MD-PSI). Updates included addition and removal of variables, as well as modification to a component calculation structure. Each component represents a major phosphorus (P) loss pathway. The UM-PMT includes a particulate-bound P (PARTICULATE), surface dissolved P (DP) (RUNOFF), and subsurface DP loss (SUBSURFACE) components. For the SUBSURFACE component, the leaching potential variable was removed and replaced with the subsurface drainage transport factor (SD) matrix (Table 1.). The matrix included soil drainage class and hydrologic soil group (HSG). Both measures were similar, as soil drainage class is the amount of time the soil is under saturated conditions (Soil_Survey_Division_Staff, 1993) and HSG is determined by the depth of the soil layer with the lowest saturated hydraulic conductivity (NRCS, 2007). The SUBSURFACE source component is calculated based on soluble P in the soil, measured by degree of P saturation (DPS), and soluble P applied as an amendment. Management factors are also included that modified the soluble P applied based on method of application, timing of application, and tillage.

These changes were made in response to recent research, which increased our understanding of how high P loads could occur through coastal plain drainage ditches (Vadas et al., 2007). The SD factor was meant to act as a proxy for the measurement of drainage intensity, which was thought to drive subsurface water movement and P transfer to ditches. Fields with frequent, shallow ditches likely have a high water table and somewhat impermeable soils. Historically, farmers would have increased ditching intensity to lower the water table enough for cultivation. Conversely, fields with less frequent, but deeper ditches probably had more permeable soils and deeper water table (King et al., 2014). In the first case, because of the frequency of ditches, the flow path to the ditch would be very shallow throughout the field. Water travelling through these shallow pathways would spend more time in contact with P saturated soils, which typically occur nearer to the surface. Often this situation coincides with confining layers, further emphasizing lateral flow. The presence of greater clay content in these fields could slow the movement of water and adsorb P, thereby decreasing the concentration of soluble P that moves to the ditch (King et al., 2014). However, the presence of reduced conditions can limit P sorption to clay particles when the soils are saturated (King et al., 2014). In the fields with deeper ditches, which are typically sandier, water would move rapidly to ditches through coarse textured soils with little P sorption capacity. In both scenarios, a high DPS would exacerbate soluble P transport.

The use of the SD factor, however, has not been evaluated as a true proxy for drainage intensity. Furthermore, the UM-PMT SUBSURFACE component source and transport factors do not account for effect of distance from the ditch on P loss. The objectives of this study were to (1) determine if distance from primary and secondary ditches and soil texture affect nutrient concentration throughout the soil profile and warrant inclusion in the UM-PMT, (2) compare nutrient concentrations through the soil profile in three similar agricultural fields, and (3) modify the SUBSURFACE component of UM-PMT, specifically the SD factor, to more accurately reflect subsurface P transport.

3.2 Materials and Methods

3.2.1 Soil collection

Deep soil samples (0-100 cm deep) were collected in a grid layout at three sites with artificial drainage present on the eastern shore of Maryland (A: 39.117409° N, -75.806988° W; B: 38.036799° N, -75.765236° W; C: 38.124972° N, -75.718151° W). Grids assigned a categorical variable representing relative distance from the primary and secondary ditches, depending on if the grid was near or far from primary and secondary ditches. Soil samples were collected using a Gidding's hydraulic probe, outfitted to collect samples to a depth of 1 m using a probe with ten cm diameter cylinder. Four intact soil cores were collected at random locations within each grid. Each soil core was removed from the probe, measured, and divided into up into five cm depth increments from 0-20 cm then ten cm increments from 20 to 100 cm. For each depth segment, the four samples were combined to form one composite sample per depth per grid. Samples were collected in the spring and fall of 2012.

3.2.2 Laboratory Analyses

Soil samples were oven dried and ground to pass through a 2 mm sieve. Samples were extracted using Mehlich 3 (1:10 soil/0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.015M NH_4F + 0.13M HNO_3 + 0.0001M EDTA, (Mehlich, 1984)) and ammonium oxalate (1:40 soil/0.2M ammonium oxalate (pH 3), 2-hr reaction time in the dark (McKeague and Day, 1966)), and P, Al, and Fe concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). In addition, water extractable P (WEP) was determined using 2 g of soil and 20 mL of deionized water by shaking on a reciprocating shaker and filtering with 0.45 μm Millipore filtration (Luscombe et al., 1979). Phosphorus concentration in the extract was determined by Lachet QuikChem 8500 Flow Injection Analysis System, Method 12-115-01-1-A (Hach Company, Loveland, CO).

Particle size analysis was performed on spring samples only using the hydrometer method (Gee and Bauder, 1986), as texture would not be expected to change between seasons. Molar concentrations of ammonium oxalate extractable P, Fe, and Al ($[P_{ox}]$, $[Fe_{ox}]$, $[Al_{ox}]$) were used to calculate degree of P saturation-oxalate (DPS_{ox}, Equation 1.5; α=0.5). The alpha value (α) provides an estimate of the proportion of the Fe and Al available for P sorption and can be determined using P sorption isotherms (Nair et al., 1984). The standard alpha value of 0.5 (Pautler and Sims, 2000; Schoumans, 2000) was used for our study. Molar concentrations of Mehlich 3 P, Fe, and Al ([M3P], [M3Fe], [M3Al]) were used to calculate Mehlich 3 P Saturation Ratio I and II (M3PSR-I and II; Equation 1.7 and Equation 1.). Mehlich 3 saturation ratios have been suggested as an additional method for DPS calculation using Mehlich 3 extraction, which is commonly performed in soil testing laboratories (Khiari et al., 2000; Pautler and Sims, 2000).

3.3 Results

3.3.1 Soil Profile Characteristics

The sampling locations were selected because concurrent research was being performed at the sites and fields were easily accessed. Location A was located in Caroline County, Maryland while locations B and C were located in Somerset County, Maryland. Location B had the highest mean concentrations in the surface (0-20cm) samples for all measures of soil P (Mehlich 3, ammonium oxalate, water extraction), while location A had the highest mean soil Fe concentrations (Table 3.1). Location A also had the lowest mean WEP concentration and greatest mean sand content in the surface samples compared to the other two sites. Clay content in the soil profiles tended to increase between 30 and 50 cm at locations B and C, with the increase more pronounced at location B (Figure 3.1). This increase in clay content could represent a confining layer, slowing water movement through the profile, demonstrated by redoximorphic features observed at a similar depth to the increased clay content (Table 3.2). This could result in a perched water table at these sites, which would increase the likelihood of lateral water and nutrient movement to nearby ditches (Reuter et al., 1998). Location A did not show changes in clay content with depth.

Soil pH decreased from spring to fall at locations B and C, with the decrease more pronounced in the surface soils at location B (Figure 3.2). Soil pH did not exhibit a clear seasonal trend at location A. Either corn or soybeans were planted and harvested between sample collection at all sites, and the exchange of nutrients between the plant and the soil could have resulted in a decrease in soil pH. Mehlich 3 and ammonium oxalate extractable P concentrations did not vary between seasons (Figure 3.3, Figure 3.4) for most locations. Mehlich 3 P at location B increased slightly from spring to fall (Figure 3.3a), but could likely be due to variation in soil collected during sampling.

All sites showed very low P concentrations below the depth of redoximorphic features (Table 3.2). Redoximorphic features represent the highest groundwater depth throughout the year and Fe-hydroxides become reduced after prolonged periods of saturation. Soil P concentrations were expected to be low in soil below the water table, as reduced forms of Fe-hyrdoxides do not adsorb P molecules as well as the oxidized forms. Results for Al and Fe concentrations from both extraction methods were similar. There was some variability among sampling grids in Al concentration and locations B and C tended to have higher soil Al concentrations. Iron tended to be more consistent through the profile at locations B and C, with greater concentration and variability at location A (Figure 3.5, Figure 3.6).

The three sampling locations represent fields on the Maryland's eastern shore that would likely have a high risk of subsurface P losses due to artificial drainage. Differences among the sites include the presence of a confining layer and a perched water table at locations B and C and difference in Al and Fe concentrations in the soil profile, with elevated soil Fe concentrations at location A. The presence of a perched water table could impede vertical water movement through the profile, but enhance lateral movement towards drainage ditches. Sorption of downward soluble P movement would occur at sites with greater clay content and soil Al and Fe concentrations in the profile, as there is greater potential for sorption of soluble P moving vertically or laterally through the profile and decreased soluble P loss (King et al., 2014).

3.3.2 Phosphorus Saturation Comparison

Measures of phosphorus saturation were compared for surface soils (0-20 cm) only, as good correlation was observed for all comparisons in the subsurface soils. Mehlich 3 P correlated well with DPS_{ox} for all locations in fall (R^2=0.5-0.8***, Figure 3.7a) and for locations A and C in Spring (R^2=0.71*** and 0.67***, respectively) but a change in M3P concentration between seasons was observed in a number of samples at location B (Figure 3.7a, circled). This population of samples identified in the figure likely caused the poor correlation between M3P and DPS_{ox} for location B in the spring. It is not expected that M3P concentration would change appreciably in the soil between seasons in one year, therefore these values may be a result of laboratory error or variability of soil collected between seasons. Water extractable P correlated well with DPS_{ox} at locations B and C (R^2=0.58-0.72***; Figure 3.7a) and PSR-I (R^2=0.71-0.85***) for all locations (Figure 3.8a). A poorer relationship was observed between WEP and DPS_{ox} at location A (R^2=0.42***) for both seasons (Figure 3.7b). A similar relationship was also observed between WEP and PSR-II for locations B and C for both seasons (R^2=0.68-0.83***; Figure 3.8b), however the relationship was weaker for both seasons at location A (R^2=0.59*** in fall, R^2=0.48*** in spring).

Despite previous reports of good correlation between WEP and PSR-I, PSR-II, and DPS_{ox} (Pautler and Sims, 2000), the high soil Fe concentration and poor correlation between WEP and DPS_{ox} at location A indicated removal of Fe concentration from P saturation calculation may not be appropriate for all locations in Maryland, as Fe comprised a large portion of potential P sorption at location A. For locations B and C, good linear correlation was observed between PSR-I and DPS_{ox} (R^2=0.81-0.91***; Figure 3.9a) and PSR-II and DPS_{ox} (R^2=0.83-0.92***; Figure 3.9b) for both seasons, which indicated these methods for determination of P saturation would generally result in values of P saturation with similar magnitude. However, poorer relationships were observed between Mehlich 3 PSRs and DPS_{ox} at location A (PSR-I, R^2=0.79*** for fall, R^2=0.49*** for spring; PSR-II, R^2=0.22*** for fall, R^2=0.07* for spring), indicating the use of different extraction methods may result in difference in estimated P saturation. Furthermore, when both Mehlich 3 PSR calculations were compared to each other, an almost perfect linear relationship was observed for locations B and C in both seasons (R^2=0.97-0.99***; Figure 3.10) with poorer relationship observed for location A (R^2=0.57-0.65***). These results further indicate the role of the soil Fe concentration in potential P sorption at location A as well as the potential for high soil Fe concentrations to be present in other agricultural fields in Maryland.

3.4 Conclusions

The three locations sampled in the current study had different soil properties, including variations of soil P, Al, and Fe concentrations, the proportion of sand, silt, and clay in soils, and the concentration of clay at mid-profile, however locations B and C were overall more similar to each other than location A.

The various methods for calculating P saturation, including PSR-I and DPS_{ox}, tended to correlate well with each other at locations B and C, with a weaker relationship observed when PSR-II was compared to the other methods of DPS calculation (PSR-I and DPS_{ox}) at location A, likely due to high soil Fe concentrations and exclusion of Fe in the PSR-II calculation. The results of the comparison of P saturation measures warrant further investigation, as soil Fe concentrations may be an important source of potential P sorption in other Maryland locations. Accuracy in estimating DPS is important for calculation of the UM-PMT, as DPS is a factor within this calculation.

The separation of soil profile samples by depth instead of soil horizon and the categorical nature of the measurement of distance from ditches may have confounded our potential to identify relationships between soil nutrient concentrations and profile depth or distance from ditches. Further research should investigate soil profile samples collected in close proximity to each other, divided by soil horizon, and inclusion of more exact measurements of distance to ditches. This sampling procedure may result in further information regarding P transport in artificially drained agricultural systems.

3.5 *Tables*

Table 3.1 Summary statistics for Mehlich 3, ammonium oxalate, and water extraction, pH determination, degree of P saturation, and particle size analysis by location for surface samples (0-20 cm)

Location	**A**			**B**			**C**		
Result Item (units)	**n†**	**Mean**	**Range**	**n**	**Mean**	**Range**	**n**	**Mean**	**Range**
Mehlich 3 P (mg kg^{-1})	120	148	45-329	120	262	82-507	120	190	45-350
Mehlich 3 Al (mg kg^{-1})	120	430	123-942	120	778	228-1503	120	801	558-1295
Mehlich 3 Fe (mg kg^{-1})	120	415	155-718	120	227	89-369	120	303	145-434
Oxalate Extractable P (mg kg^{-1})	120	312	81-623	120	424	199-621	120	358	116-552
Oxalate Extractable Al (mg kg^{-1})	120	386	173-828	120	749	379-1225	120	649	416-1033
Oxalate Extractable Fe (mg kg^{-1})	120	1222	269-2947	120	448	315-656	120	848	442-1535
pH	120	6.49	5.01-7.36	120	5.62	5.00-6.18	120	5.85	5.16-6.78
DPS$_{ox}$‡ (%)	120	40	9-78	120	73	28-107	119	50	16-89
Water extractable P (mg kg^{-1})	120	6.96	0.93-15.38	120	14.83	1.67-35.00	120	10.48	1.56-24.52
Sand (g kg^{-1})	60	78	51-92	48	60	45-75	60	67	51-89
Silt (g kg^{-1})	60	13	4-27	48	26	6-35	60	22	3-42
Clay (g kg^{-1})	60	9	3-24	48	14	6-21	60	11	2-18

† Experimental procedures were performed on all samples in dataset, for both seasons, while soil texture was determined on samples collected in spring only, as texture did not change between seasons.

‡ Degree of phosphorus saturation, calculated as $[P_{ox}]/0.5*([Al_{ox}]+[Fe_{ox}])$

Table 3.2 Depth to redoximorphic features for each sampling grid at each location in centimeters

Location	A			B			C		
Sample Grid	Near†	Mid-distance†	Far†	Near†	Mid-distance†	Far†	Near†	Mid-distance†	Far†
Nearest to Field Ditch – Left	-40	-40	-40	-40	-20	-20	-30	-30	-20
Nearest to Field Ditch – Center Left	-30	-30	-30	-40	-40	-30	-30	-30	-30
Furthest from Field Ditch	-30	-30	-30	-40	-30	-40	-40	-40	-40
Nearest to Field Ditch – Center Right	-30	-30	-30	-30	-20	-50	-30	-30	-30
Nearest to Field Ditch – Right	-30	-30	-40	-30	-20	-40	-30	-30	-30

†Distance from main ditch

3.6 Figures

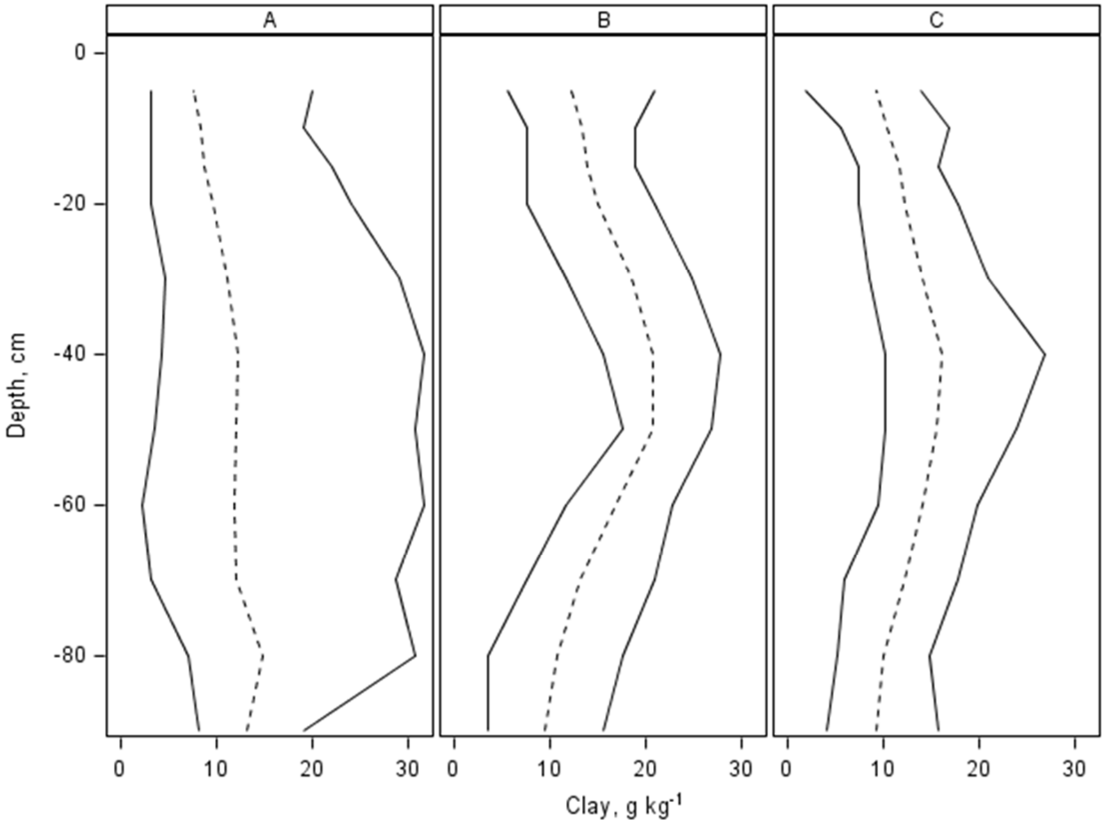

Figure 3.1 Mean (dashed line) and range of clay content in g kg^{-1} by depth at each location (A-C).

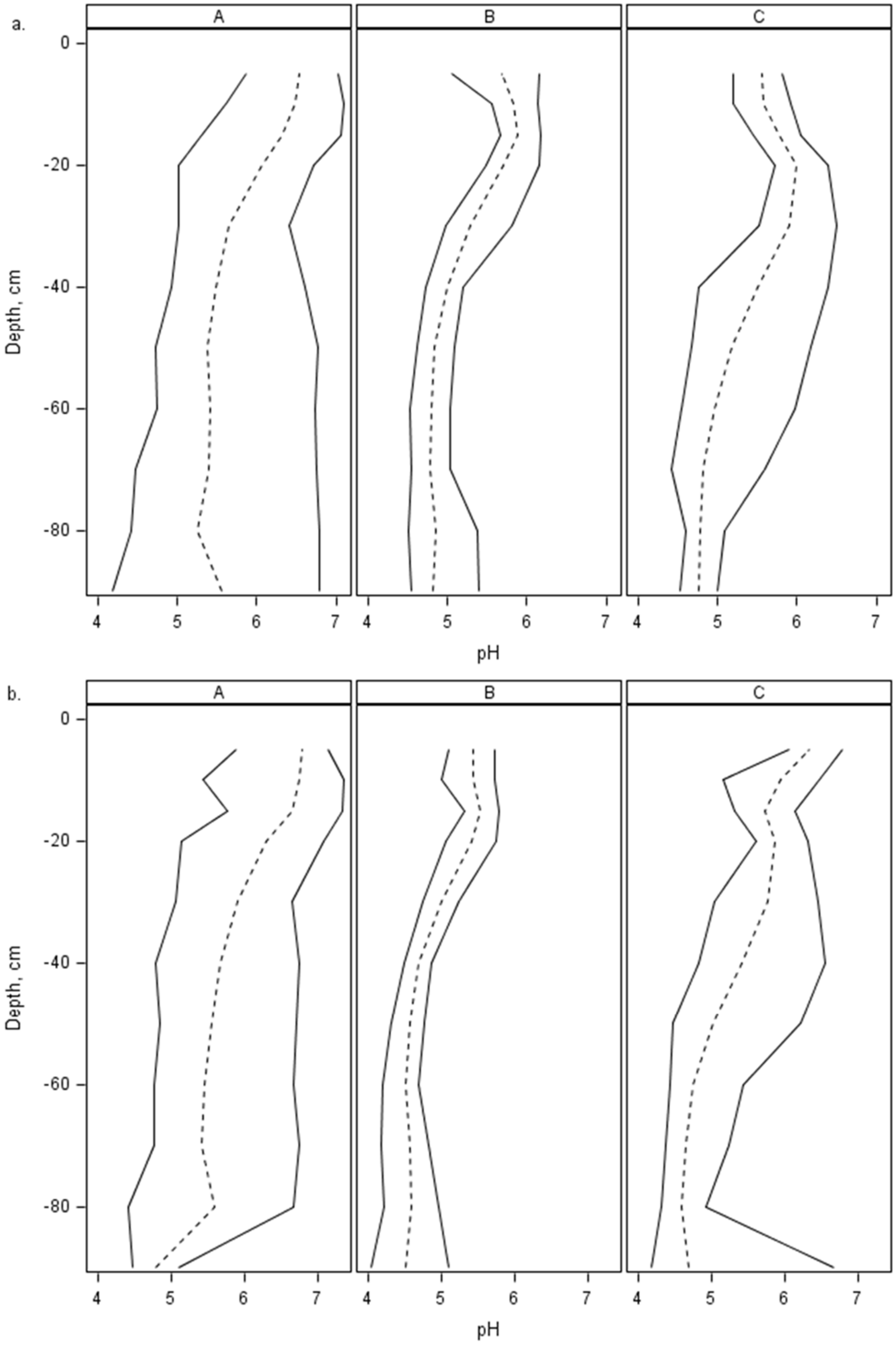

Figure 3.2 Mean (dashed line) and range of soil pH by depth for each sampling location (A-C) for (a) Spring and (b) Fall

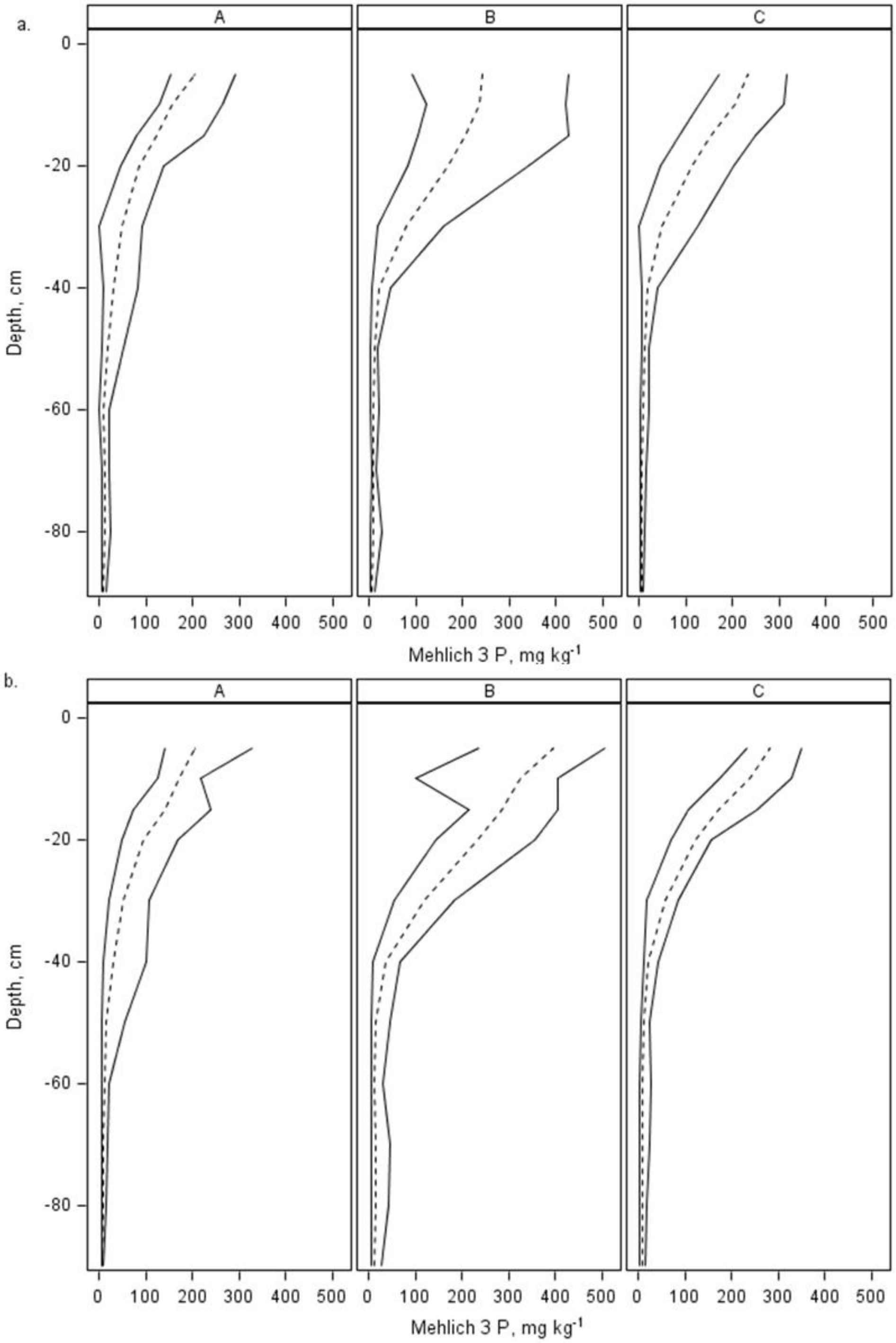

Figure 3.3 Mean (dashed line) and range of soil Mehlich 3 phosphorus concentration by depth at each location (A-C) for (a) Spring and (b) Fall

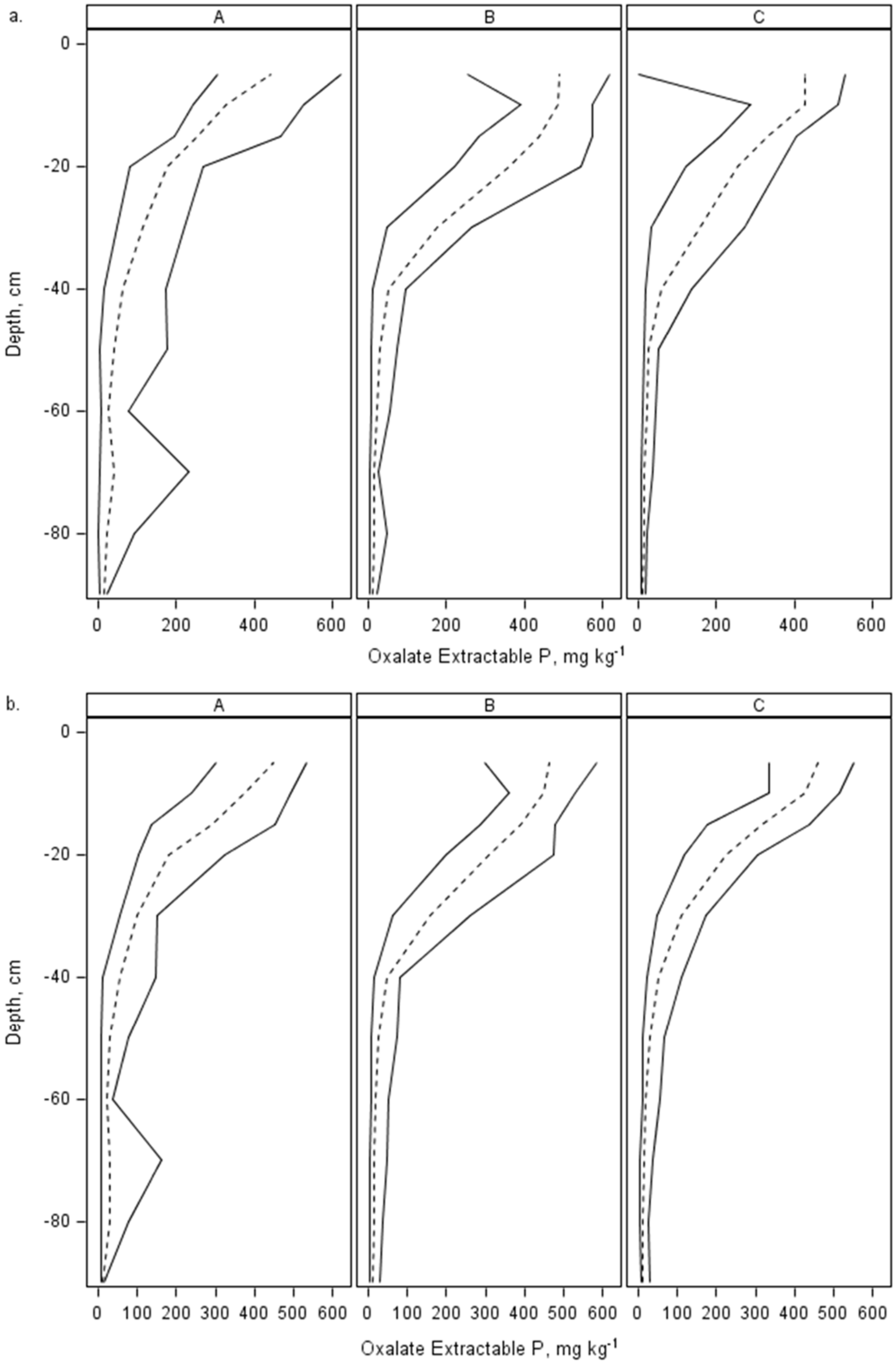

Figure 3.4 Mean (dashed line) and range of soil ammonium oxalate extractable phosphorus concentration by depth at each location (A-C) for (a) Spring and (b) Fall

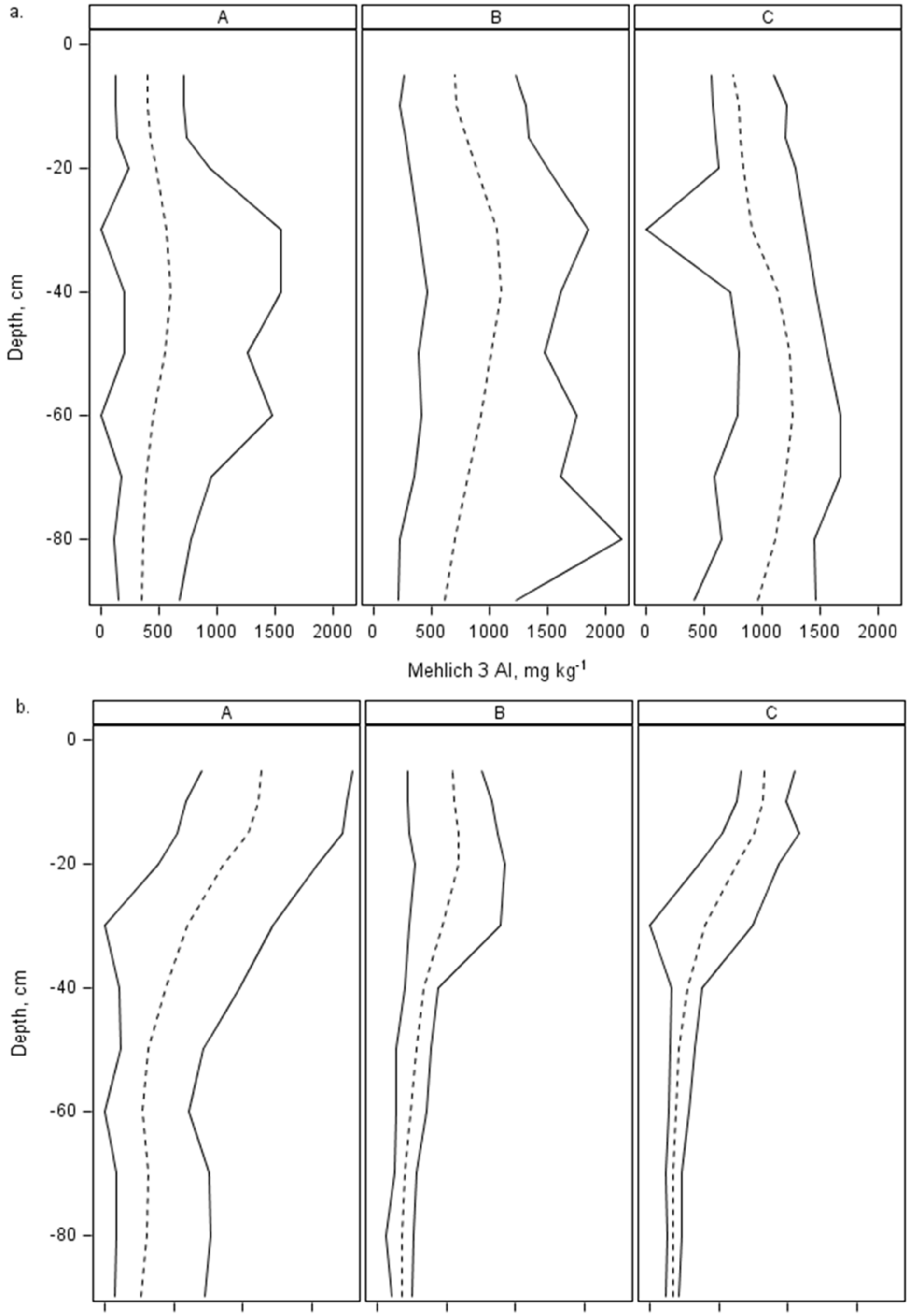

Figure 3.5 Mean (dashed line) and range of Mehlich 3 extractable aluminum (a) and iron (b) by depth at each location (A-C)

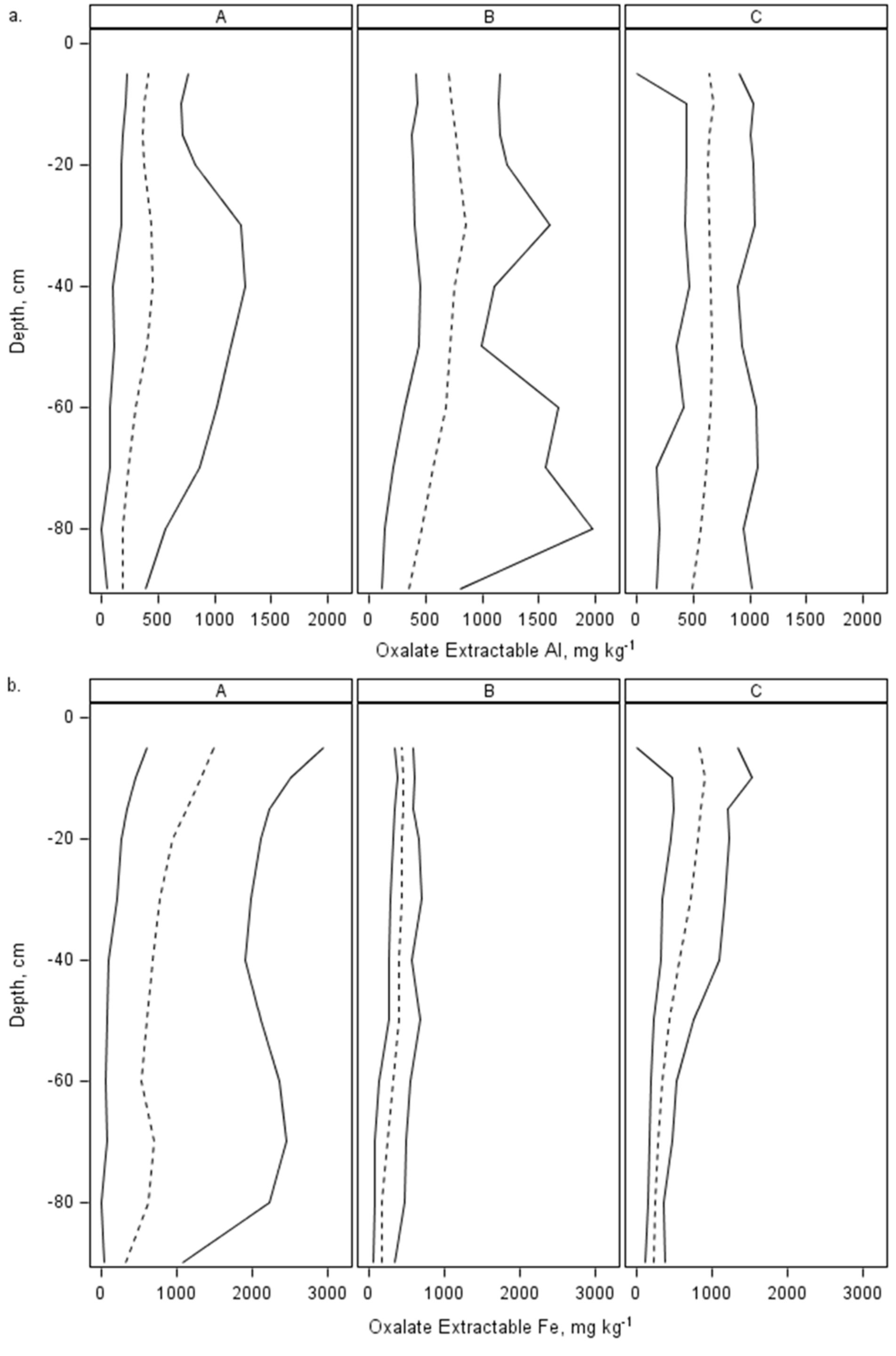

Figure 3.6 Mean (dashed line) and range of ammonium oxalate extractable aluminum (a) and iron (b) by depth at each location (A-C)

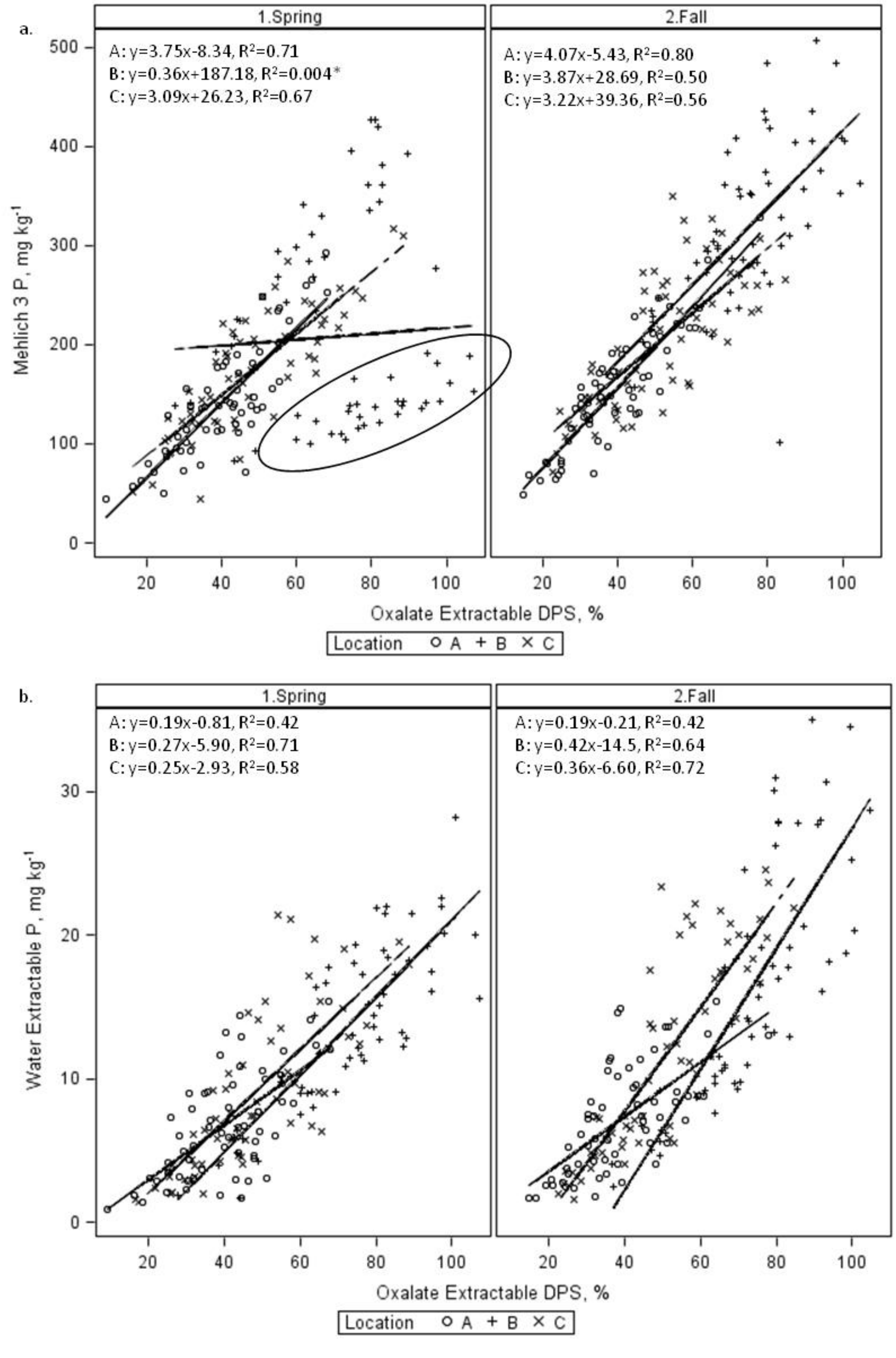

Figure 3.7 Oxalate extractable degree of phosphorus saturation (DPS, $[P_{ox}]/0.5[Al_{ox}]+[Fe_{ox}]$) versus (a) Mehlich 3 P in mg kg^{-1} and (b) water extractable P in mg kg^{-1} for surface soils (0-20 cm) by location for two season within one year. All regression equations significant at *$P< 0.0001$* except noted (*, not significant, *$P=0.62$*).

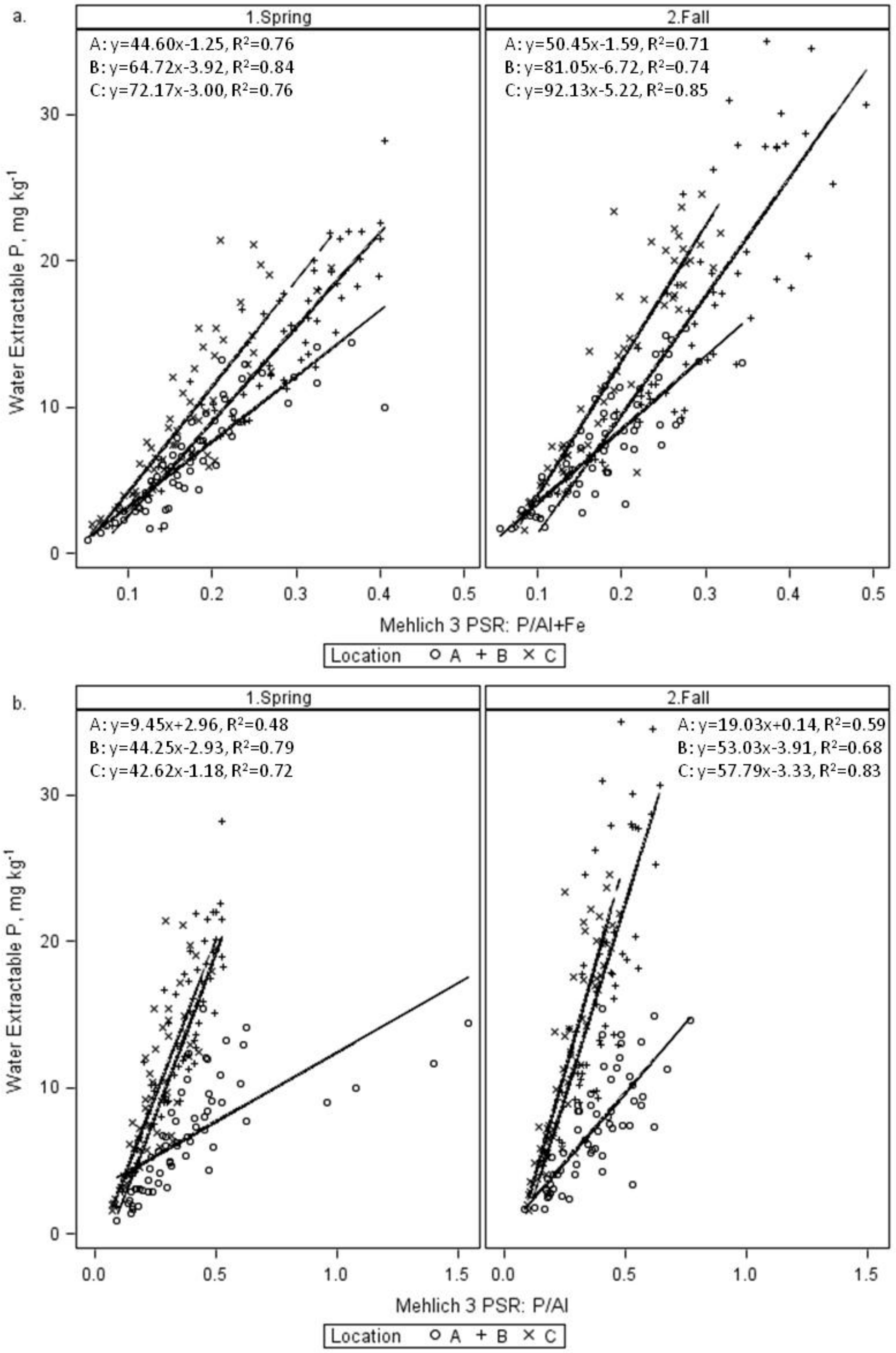

Figure 3.8 (a) Mehlich 3 P Saturation Ratio I (M3PSR-I, [M3P]/[M3Al]+[M3Fe]) and (b) Mehlich 3 P Saturation Ratio II (M3PSR-II, [M3P]/[M3Al]) versus water extractable P in surface soils (0-20 cm) by location for two seasons in one year. All regression equations significant at *P< 0.0001.*

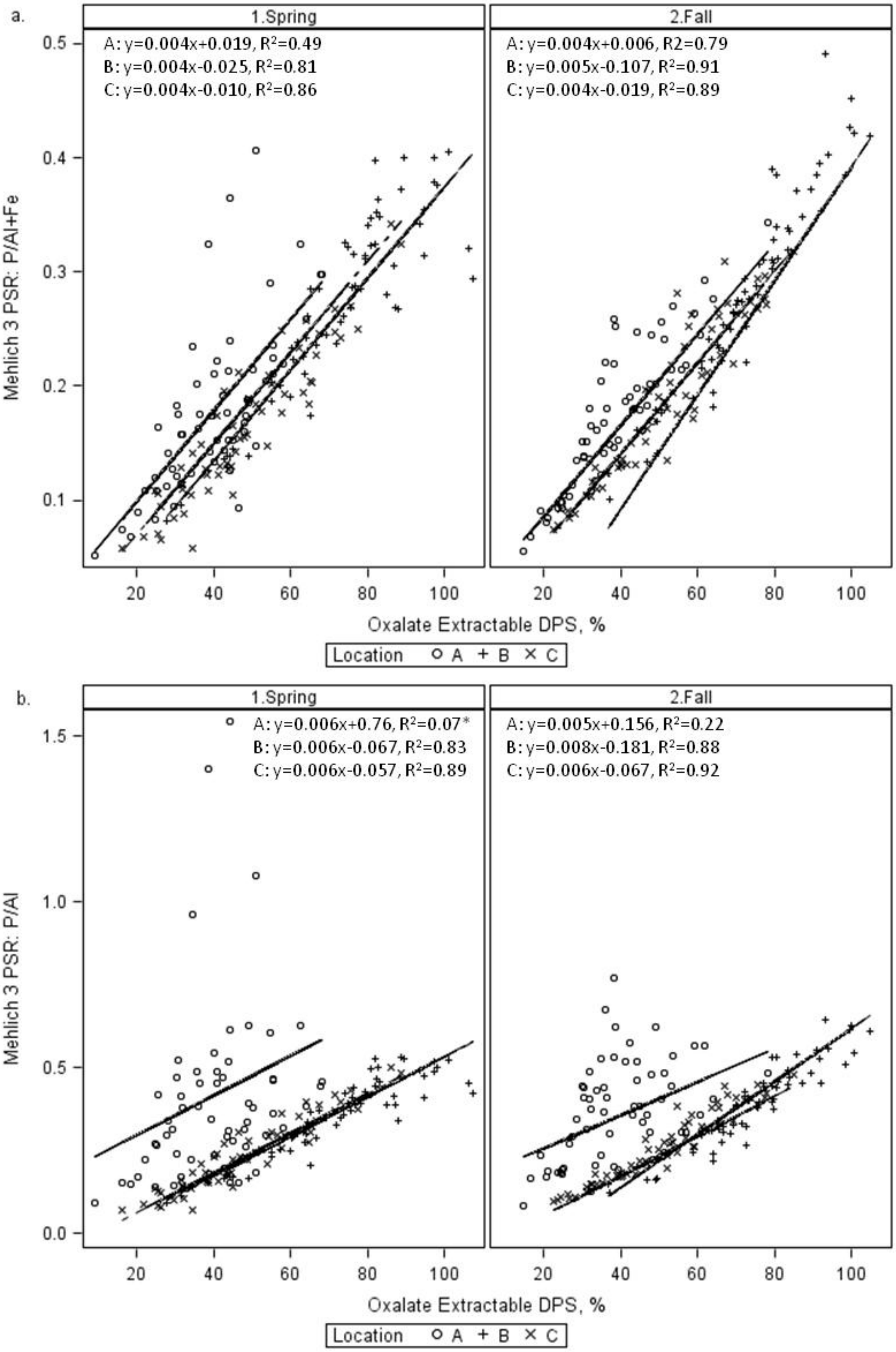

Figure 3.9 Oxalate extractable degree of P saturation (DPS, $[P_{ox}]/0.5[Al_{ox}]+[Fe_{ox}]$) versus (a) Mehlich 3 P Saturation Ratio I (M3PSR-I, [M3P]/[M3Al]+[M3Fe]) and (b) Mehlich 3 P Saturation Ratio II (M3PSR-II, [M3P]/[M3Al]) for surface soils (0-20 cm) by location (L, Lewis, M, Marion, S, Swift) for two seasons in one year. All regression equations significant at *P< 0.0001* except where noted (*, *P=0.0429*).

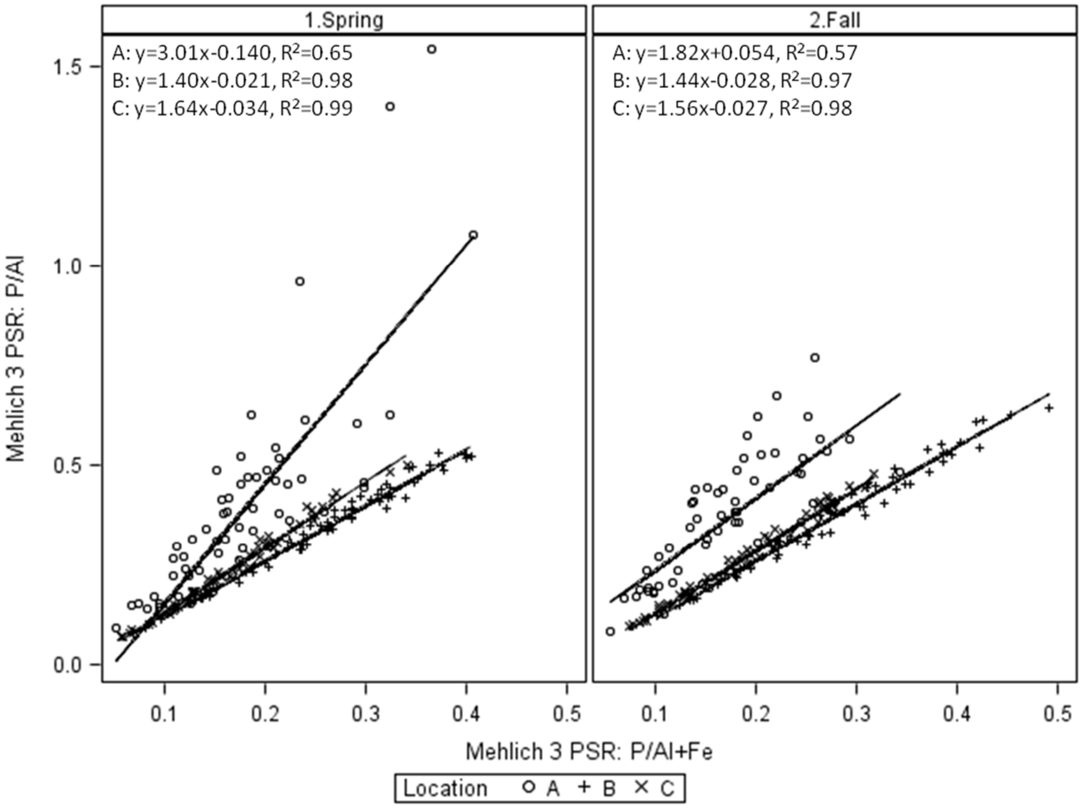

Figure 3.10 Mehlich 3 P Saturation Ratio I (M3PSR-I, [M3P]/[M3Al]+[M3Fe]) versus Mehlich 3 P Saturation Ratio II (M3PSR-II, [M3P]/[M3Al]) for surface soils (0-20 cm) by location for two seasons in one year. All regression equations significant at *P< 0.0001*.

Chapter 4. Effect of Degree of Phosphorus Saturation Method on UM-PMT Final Score

4.1 Introduction

The Phosphorus Site Index (PSI) was developed in the United States in 1993 to determine relative risk of contribution of phosphorus (P) to surface water from agricultural fields (Djodjic et al., 2002; Lemunyon and Gilbert, 1993; Mallarino et al., 2002; Sharpley et al., 2003). The basic concept of the PSI was there must be both a source and transport pathway present for there to be P loss from field to surface water. Recent modifications have been made to the Maryland PSI (MD-PSI), including a transition from a multiplicative structure to a component structure. The component model of the UM-PMT v.2 calculates risk of the P loss from the three P loss pathways: surface particulate (PARTICULATE), surface dissolved P (DP) (MANURE DP and SOIL DP), and subsurface DP loss (SUBSURFACE), with each P loss component calculation utilizing unique P source and transport factors specific to each loss pathway. The new index is referred to as the University of Maryland Phosphorus Management Tool (UM-PMT). Additional modifications have been made to the UM-PMT based on comparison of UM-PMT to modeled P loss data, which resulted in UM-PMT Version 2 (UM-PMT v.2). The UM-PMT v.2 also contains unique weighting factors calculated for each P loss component.

One major modification from the MD-PSI to the UM-PMT v.2 is the inclusion of degree of phosphorus saturation (DPS) as a source factor for both the SOIL DP and SUBSURFACE components (McGrath et al., 2013). The use of DPS in the UM-PMT v.2 replaces the use of soil test P (generally as Mehlich 3-P) as the source factor for DP loss. Studies published since the inception of the MD-PSI have concluded DPS is a better environmental soil test to predict potential P loss from agricultural fields than agronomic soil P concentrations measured by Mehlich 3 extraction (Maguire and Sims, 2002; Pautler and Sims, 2000; Sims et al., 2002).

Phosphate in the soil is commonly adsorbed to Al- and Fe-hydroxides. Therefore, methods to estimate DPS generally use a ratio of soil P to the sum of soil Al and Fe. Many methods use an ammonium oxalate extraction to determine soil P, Al, and Fe concentrations (Al_{ox}, Fe_{ox}, P_{ox}), which extracts amorphous Fe and Al that are the result of weathering (McKeague and Day, 1966). Van der Zee and van Riemsdijk (1988) proposed using an alpha value to relate the total P sorption capacity of a soil to some proportion of the sum of Fe_{ox} and Al_{ox} concentrations. Phosphorus sorption isotherm experiments are used to calculate this value (Nair et al., 1984). The isotherm data are also used with a nonlinear adsorption model (typically Freundlich or Langmuir) to determine the remaining sorption capacity (PSC_r) of the soil (van der Zee and van Riemsdijk, 1988). Once PSC_r is determined, alpha value is calculated using Equation 1.6.

An alpha value of 0.5 is typically used because measurement of P sorption isotherms is time consuming and expensive. This value was determined experimentally on Coastal Plains soils in Delaware and similar soils from the Netherlands (Pautler and Sims, 2000; Schoumans, 2000). Soil testing laboratories typically perform Mehlich 3 extraction on soil samples, and it has been previously shown the ratio of Mehlich 3 P to the sum of Al and Fe ([M3P], [M3Al], [M3Fe]) can be used to predict potential risk of P loss to the environment (Equation 1.7; (Khiari et al., 2000)). Sims et al. (2002) developed a linear relationships between Mehlich 3 P saturation ratios (M3PSR) and oxalate extractable DPS_{M3} (Equation 1.). The University of Delaware Soil Testing Laboratory uses this conversion for calculating DPS and McGrath et al. (2013) recommended its use in the UM-PMT.

The various methods for estimating DPS are related, but may result in numerically different values due to methodological differences or simply arithmetic differences. Nonetheless, they all estimate the relative saturation of a specific soil in regard to its total P sorption capacity. However, because they differ numerically, two different DPS estimates could result in widely different UM-PMT v.2 final scores. Changes to UM-PMT v.2 final score could have major implications for producers throughout Maryland, whose P amendment applications are regulated based on PSI final score. Therefore, the objectives of this study were to (1) investigate the magnitude of change in DPS value when using multiple methods for calculation and (2) compare the magnitude of change in DPS value to magnitude of change in UM-PMT v.2 final score.

4.2 Materials and Methods

4.2.1 Soil Sample Collection and Extraction

Surface soil samples (0 to 20 cm, n=380) were collected from agricultural fields within each county in Maryland between 2011 and 2012. Soil samples were oven dried and ground to pass through a 2 mm sieve. Samples were analyzed for Mehlich 3 (1:10 soil/0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.015M NH_4F + 0.13M HNO_3 + 0.0001M EDTA, (Mehlich, 1984)), ammonium oxalate (1:40 soil/0.2M ammonium oxalate (pH 3), 2-hr reaction time in the dark (McKeague and Day, 1966)) extractable P, Al, and Fe concentrations by inductively coupled plasma atomic emission spectroscopy (ICP-AES), and water extractable P (WEP, 1:10 soil/deionized water, 1-h reaction time, 0.45 μm Millipore filtration (Luscombe et al., 1979)) by Lachet QuikChem 8500 Flow Injection Analysis System, Method 12-115-01-1-A (Hach Company, Loveland, CO). Seven-point

P sorption isotherms ((Nair et al., 1984); 0, 0.1, 1, 5, 10, 35, 50 mg P L^{-1} as KH_2PO_4) were performed on a subset of soils (n=33) which consisted of high, moderate, and low concentrations of M3Fe, M3Al, M3Fe+M3Al, Fe_{ox}, Al_{ox}, Fe_{ox}+Al_{ox} with a high and low P concentration sample in each of those groupings. Phosphorus sorption isotherms entail equilibrating a soil sample in a range of known P concentrations and measuring the concentration of P remaining in each solution after a determined equilibration time at a constant temperature. Phosphorus sorption maxima were calculated by fitting the non-linear Langmuir equation to the isotherm data for each sample using PROC NLIN in SAS 9.3 (SAS Institute, 2009).

4.2.2 Degree of Phosphorus Saturation Calculations

Five different methods for estimating DPS were compared for each field in the dataset. First, DPS was calculated by ammonium oxalate extraction ($DPS_{0.5}$, Equation 1.5; (van der Zee and van Riemsdijk, 1988)) with alpha equal to 0.5. The $DPS_{Langmuir}$ was determined for the subset soils using Equation 1.5 and calculated alpha values from Equation 1.6. Mehlich 3 P saturation ratio was calculated using two different methods, first as the ratio of M3P to the sum of M3Fe and M3Al (M3PSR-I, Equation 1.7) and next, by removal of the M3Fe concentration (M3PSR-II, Equation 1., (Khiari et al., 2000)).

The current DPS calculation recommended for use in the UM-PMT v.2 is the linear conversion of M3PSR-I to ammonium oxalate extractable DPS (DPS_{M3}) using Equation 1. (Sims et al., 2002). Final score for UM-PMT v.2 was calculated for each field using each of the DPS calculation methods. The values for both M3PSR ratios multiplied by 100 so values were the same order of magnitude as DPS_{M3}, $DPS_{0.5}$, and $DPS_{Langmuir}$, and final scores were assigned to corresponding interpretive category (Table 1.7).

4.3 Results and Discussion

4.3.1 Soil Properties

Soils used in this study were collected from agricultural fields across Maryland, with every county represented in the dataset (Table 2.1). Soil organic matter ranged from 0.7 to 11.3 g kg^{-1} and clay from 3.2 to 42.8 g kg^{-1} (Table 4.1). Clay content increased moving from west to east or from mountain and piedmont to Coastal Plains. Previous studies that have investigated DPS have often focused on Coastal Plains soils that tend to have higher sand content with low organic matter content and pH (Maguire and Sims, 2002; Pautler and Sims, 2000; Sims et al., 2002). Mean M3PSR values were 0.21 for M3PSR-I and 0.24 for M3PSR-II. Mean values for the three DPS methods were also similar, DPS_{M3} was 54, $DPS_{0.5}$ was 49, and $DPS_{Langmuir}$ was 44 (Table 4.2).

Mehlich 3 extractable P, Al, and Fe were regressed against their respective oxalate extractable element (Figure 4.1), with linear relationships observed for Fe ($y=0.06x + 162$, $R^2=0.32$***) and P ($y=0.38x + 82$, $R^2=0.38$***), and a curvilinear relationship observed for Al ($y=62.6x^{0.38}$, $R^2=0.53$***). Maguire and Sims (2002) also observed a power regression for Al concentrations in their data, although they observed a higher R^2 value. Both Sims et al. (2002) and Maguire and Sims (2002) reported greater R^2 values for the regression equations for P and Fe. This may be attributed to the soils, which were Coastal Plains soils compared to the greater texture diversity in the soils used in the current study. This diversity in textures contributed to greater variability in Al, Fe, and P concentrations, which might have contributed to lower R^2 values for their comparison.

A linear relationship was observed between $DPS_{0.5}$ and WEP or M3P (WEP: $y=0.22x-3$, $R^2=0.62$***; M3P: $y=4.29x+2.64$, $R^2=0.52$***; Figure 4.2) while $DPS_{Langmuir}$

had an exponential relationship with WEP or M3P (WEP: $y=1.97e^{0.03x}$, $R^2=0.92^{***}$; M3P: $y=68e^{0.03x}$, $R^2=0.81^{***}$; Figure 4.2). Despite a smaller sample size, there was a stronger curvilinear relationship observed for the $DPS_{Langmuir}$ plots than a linear relationship for the $DPS_{0.5}$ plots. However, the exponential relationships indicated $DPS_{Langmuir}$ related well to WEP and M3P at lower soil P concentration but the relationship did not hold as soil P concentrations increased. The relationships between WEP and P_{ox} ($y=0.01x+3.56$, $R^2=0.16^{***}$) and M3P and P_{ox} ($y=0.41x+69.5$, $R^2=0.42^{***}$) were linear, but the relationships weakened for both comparisons as P concentrations increased. The P_{ox} represents P adsorbed to amorphous Al and Fe while WEP represents the portion of the total P that is soluble in the soil. In a soil that is P saturated, a greater proportion of the total P pool would be soluble. So as a soil approaches P saturation, the rate of increase of WEP would be greater than the rate of increase for P_{ox}, which would result in a range of WEP values for one $DPS_{Langmuir}$ value.

Alpha value for $DPS_{Langmuir}$ was calculated as the ratio of total P sorption capacity (PSC_t) to the sum of Al_{ox} and Fe_{ox}. A good correlation relationship between $Al_{ox}+Fe_{ox}$ and PSC_t was observed for the subset soils (Figure 4.3) and with a greater correlation coefficient than previously reported (r=0.76 in the current study vs. r=0.61 from Pautler and Sims (2000)). Following Pautler and Sims (2000), a new alpha value was calculated for the current dataset by multiplying the mean alpha value calculated for the subset soils (mean alpha=0.57) and multiplying by 1.8, to adjust for slow sorption kinetics in the absence of performing the sorption isotherm experiment over a longer time period (249 d). This extended time period sorption isotherm was originally reported by van der Zee and van Riemsdijk (1988). When accounting for slow sorption kinetics, the calculated alpha value in the current study was 1.03 and $DPS_{1.03}$ was calculated for all fields, using Equation 1.5 and substituting 1.03 as the alpha value.

4.3.2 Comparison of Degree of Phosphorus Saturation Methods of Calculation

The M3PSR-I and M3PSR-II values correlated well with each other (y=0.0041x+0.0037, R^2=0.98***) and these results were similar to previously published results (Khiari et al., 2000; Maguire and Sims, 2002; Sims et al., 2002). Sims et al. (2002) developed Equation 1. by regressing $DPS_{0.5}$ and M3PSR-I for their dataset of soils which represents Mid-Atlantic soils used in agricultural systems. A good relationship was observed between $DPS_{0.5}$ and M3PSR-I for the current dataset, however R^2 value was not as high as previously found (R^2=0.84*** [Figure 4.4a] vs. R^2=0.98 for Sims et al. (2002)). A good regression relationship was also observed between $DPS_{0.5}$ and M3PSR-II (R^2=0.84***; Figure 4.4b) for the current dataset. When $DPS_{Langmuir}$ was compared to M3PSR-I and M3PSR-II, R^2 was higher than the relationship with $DPS_{0.5}$ however there was a better exponential relationship than linear relationship (Figure 4.4c-d). Similar to $DPS_{Langmuir}$ relationship with WEP and M3P, the regression between $DPS_{Langmuir}$ and M3PSR-I and M3PSR-II is valid at low M3PSR values, but does not hold well as values increase.

Since the UM-PMT currently recommends the use of DPS_{M3} method for predicting DPS_{ox} from Mehlich 3 extractable P, Al, and Fe, the other methods of DPS calculation were compared to the DPS_{M3} method. Since DPS_{M3} calculation is determined from M3PSR-I, a perfect correlation was calculated between the two methods, however a very good correlation was also calculated between DPS_{M3} and M3PSR-II (y=0.005x-0.034, R^2=0.98***). When DPS_{M3} was compared to the oxalate extractable methods of calculating DPS ($DPS_{0.5}$ and $DPS_{Langmuir}$), a better relationship was observed between

DPS_{M3} and $DPS_{0.5}$ (R^2=0.84***, Figure 4.5a) than between DPS_{M3} and $DPS_{Langmuir}$ (R^2=0.56***, Figure 4.5b). Data are not shown for comparison of $DPS_{1.03}$ to other DPS methods, as R^2 values were identical to comparisons with $DPS_{0.5}$.

Linear relationships were observed between the current DPS method used in the UM-PMT v.2 (DPS_{M3}) and other methods of DPS calculation, namely M3PSR-I, M3PSR-II, and $DPS_{0.5}$, $DPS_{1.03}$. A power relationship was observed when DPS_{M3} was compared to the $DPS_{Langmuir}$ method. The $DPS_{Langmuir}$ method exhibited exponential relationships with other DPS methods as well, including M3PSR-I and M3PSR-II, while $DPS_{0.5}$ and $DPS_{1.03}$ exhibited linear relationships with the M3PSRs. These results indicate M3PSRs and DPS_{ox} methods are able to calculate P saturation beyond 100%, identifying soils that are beyond saturation with P, while the $DPS_{Langmuir}$ method can never result in P saturation above 100%. Since the M3PSRs and $DPS_{0.5}$ are meant to estimate $DPS_{Langmuir}$, these data indicate the equations do not estimate $DPS_{Langmuir}$ well in highly saturated soils.

4.3.3 UM-PMT Final Score and DPS Calculation Methods

Final score for UM-PMT v.2 using DPS_{M3} was compared to UM-PMT v.2 final score calculated using the other DPS methods. When UM-PMT v.2 was calculated using $DPS_{0.5}$ and $DPS_{Langmuir}$ the final scores were numerically different than UM-PMT v.2 final scores calculated using DPS_{M3} (Figure 4.6), however nearly all fields fell into the same interpretive category. Conversely, UM-PMT v.2 final scores calculated using M3PSR-I, M3PSR-II, and $DPS_{1.03}$ showed numerical and interpretive category differences (Figure 4.) compared to UM-PMT v.2 final score calculated using DPS_{M3}. For a number of fields, the final score for UM-PMT v.2 calculated using DPS_{M3} was categorized into the HIGH category while the final score for UM-PMT v.2 was categorized as MEDIUM using one of the other DPS calculation methods. This was observed for 15%, 14%, and 8% of fields where UM-PMT v.2 final score was calculated using M3PSR-I, M3PSR-II, and $DPS_{1.03}$, respectively (Figure 4.).

The methods investigated for calculating DPS showed good correlation with each other. Despite good correlation, the numerical differences between the methods translated to categorical differences in UM-PMT v.2 final score, which impacts management recommendations and P amendment application for fields with high scores.

4.4 Conclusions

Results from this study indicate M3PSRs, $DPS_{0.5}$, and $DPS_{1.03}$ had strong, linear relationships with one another. Curvilinear relationships were observed when comparing $DPS_{Langmuir}$ to measures of soil P concentration and M3PSRs, $DPS_{0.5}$, and $DPS_{1.03}$, indicating the relationship grew weaker as soil P concentration increased. Despite good linear relationship, numerical differences between M3PSRs, $DPS_{1.03}$, and DPS_{M3} were large enough to affect UM-PMT v.2 final scores and interpretive categories, which give recommendations for P amendment application and management. The effect of DPS method was most pronounced on fields in the Lower Shore region of Maryland.

If a measure of DPS was used to determine application of P amendments in place of a P risk assessment tool such as the UM-PMT v.2, the results of the present study indicated DPS calculation would impact P application to agricultural fields. However, when DPS is used in the context of the UM-PMT v.2 or other PSI, the final score of the index would be scaled against P loading data, so DPS value would be similarly scaled. Therefore, numerical differences between DPS calculation methods would not result in drastic differences in management recommendations. Further research should be conducted on the relationship between DPS and P loss through subsurface pathways in order to appropriately weigh this source factor in the UM-PMT v.2. Furthermore, research to quantify the uncertainty surrounding UM-PMT v.2, its inputs, and the economic and environmental cost of this uncertainty is needed.

4.5 Tables

Table 4.1 Organic matter and clay content, water extractable phosphorus (WEP), and Mehlich 3 and ammonium oxalate extractable P, iron (Fe), and aluminum (Al) of soils in the complete dataset (n=380) and subset (n=33) of soils where phosphorus isotherms were conducted

	All Soils, n=380			**Isotherm Soils, n=33**		
Soil Property	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
Organic matter, g kg^{-1}	2.67	1.33	0.7-11.3	3.08	1.55	1.1-8.1
Clay content, g kg^{-1}	15.7	7.7	3.2-42.8	16.7	8.0	3.6-33.6
WEP, mg kg^{-1}	7.43	6.04	0.21-30.9	7.54	8.10	0.34-28.1
	Mehlich 3, mg kg^{-1}					
P	211	131	9-854	236	244	25-854
Al	829	228	143-1697	907	308	478-1697
Fe	224	98	71-673	225	125	71-652
	Ammonium Oxalate, mg kg^{-1}					
P	342	219	26-1440	370	368	27-1440
Al	909	499	44-3192	929	566	105-2400
Fe	1021	832	45-5348	1059	995	58-5106

Table 4.2 Summary of DPS values calculated using the five methods

Method	**n**	**Mean**	**SD**	**Range**
M3PSR-I	380	0.21	0.17	0.009-0.57
M3PSR-II	380	0.24	0.23	0.01-0.66
DPS_{M3}	380	54	42	7-140
$DPS_{0.5}$	380	49	25	11-228
$DPS_{Langmuir}$	31	44	22	8-83

4.6 Figures

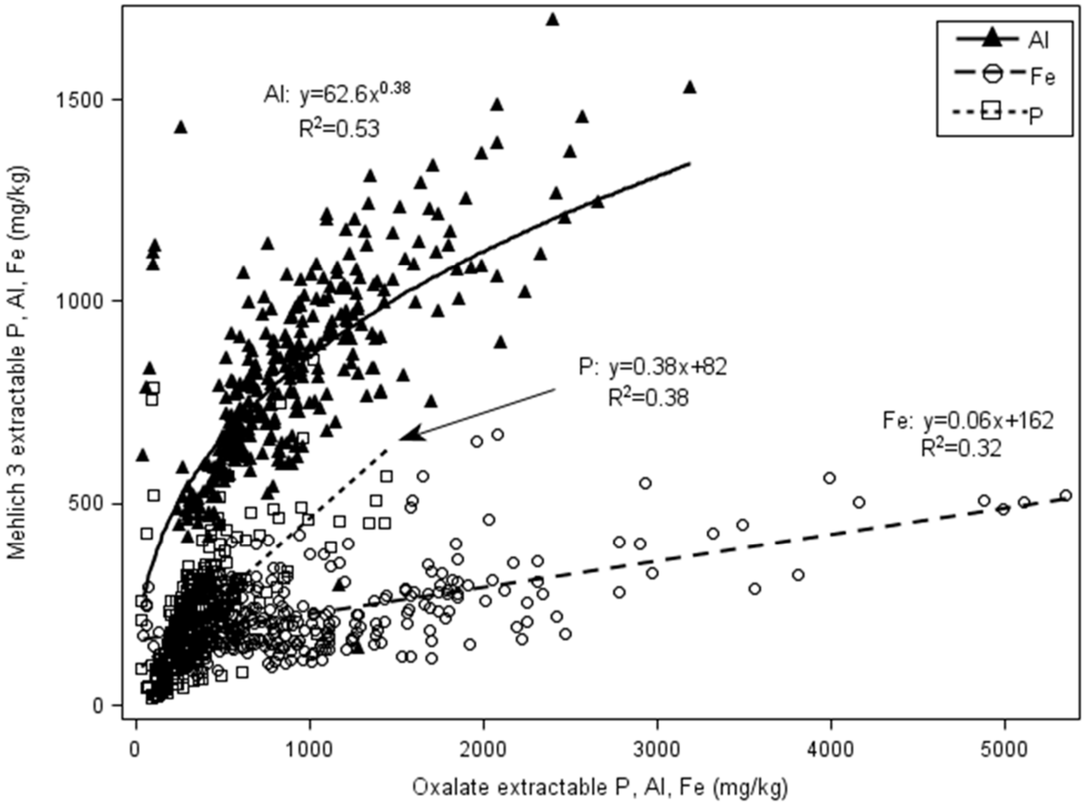

Figure 4.1 Comparison of soil concentrations of Al, Fe, and P extracted with ammonium oxalate and Mehlich 3 extractions. All regression equations significant at P<0.0001

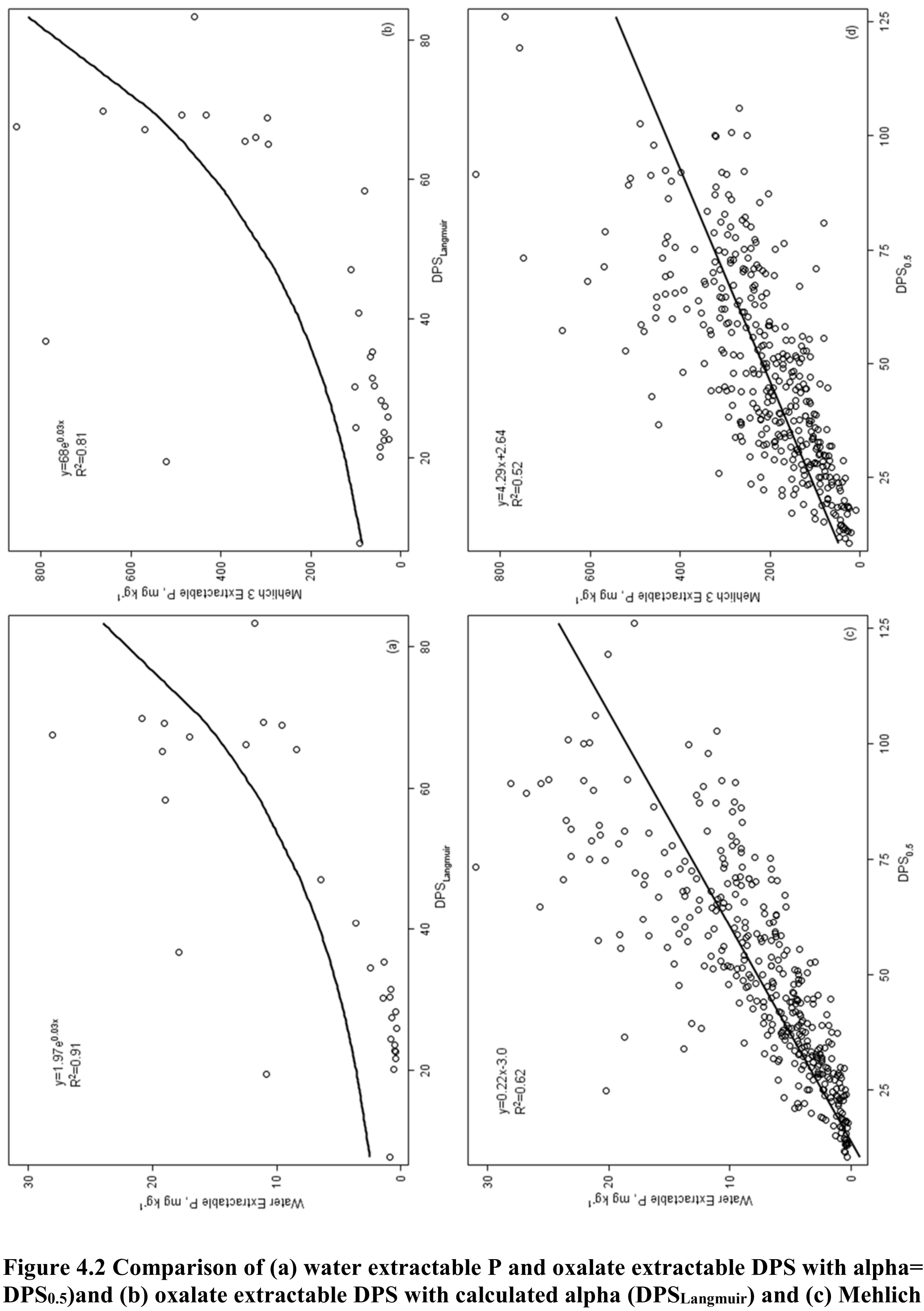

Figure 4.2 Comparison of (a) water extractable P and oxalate extractable DPS with alpha=0.5 ($DPS_{0.5}$)and (b) oxalate extractable DPS with calculated alpha ($DPS_{Langmuir}$) and (c) Mehlich 3 extractable P and $DPS_{0.5}$ and (d) $DPS_{Langmuir}$ for soils with $DPS_{0.5}$<200. All regressions significant at P<0.0001

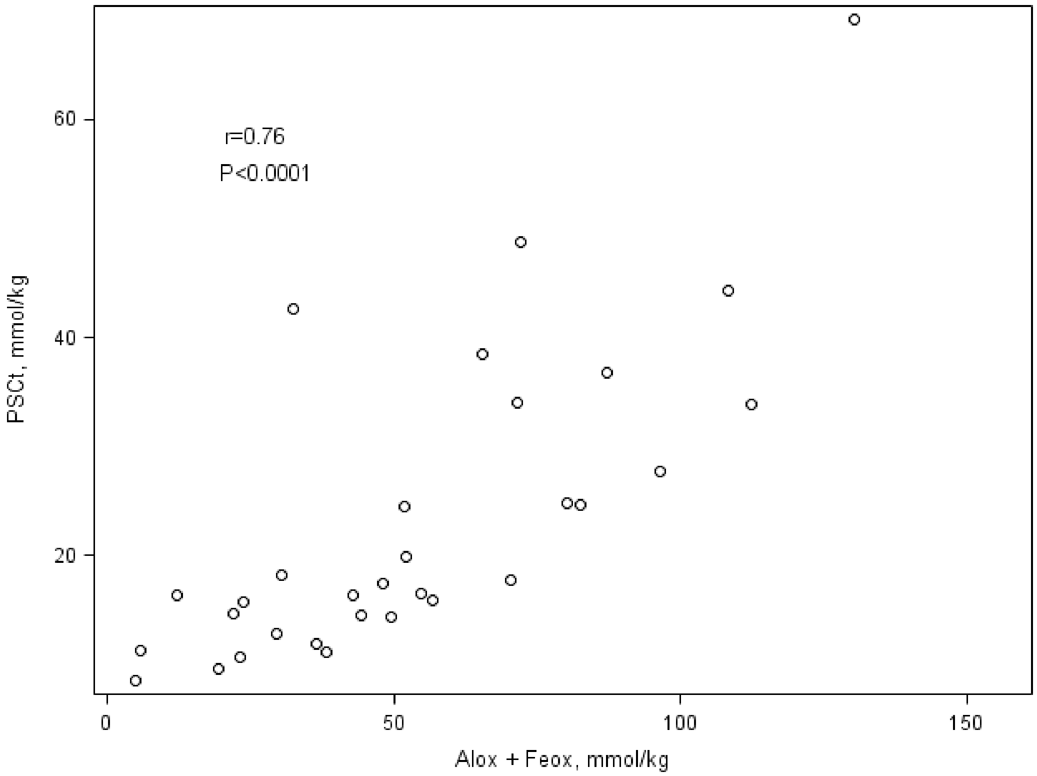

Figure 4.3 Comparison of the sum of oxalate extractable Al and Fe to total P sorption (PSC_t) determined using Equation 1.5.

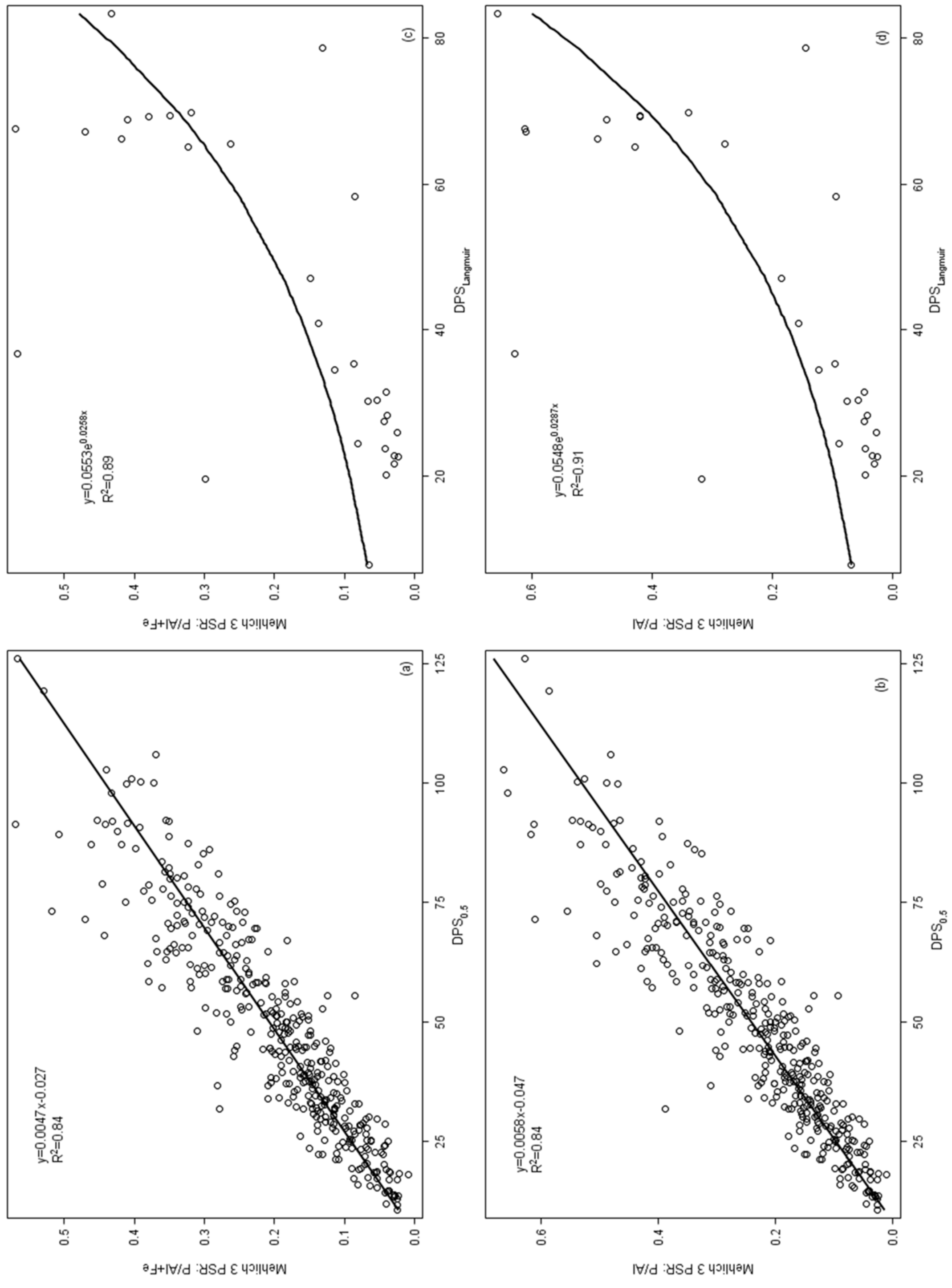

Figure 4.4 Comparison of (a) oxalate extractable DPS with alpha=0.5 ($DPS_{0.5}$) and Mehlich 3 P Saturation Ratio I (M3PSR-I, [M3P]/[M3Al]+[M3Fe]) and (b) Mehlich 3 P Saturation Ratio II (M3PSR-II, [M3P]/[M3Al]) (C) oxalate extractable DPS with calculated alpha ($DPS_{Langmuir}$) and M3PSR-I and (d) M3PSR-II for samples with $DPS_{0.5}$ < 200. All regressions significant at P<0.0001.

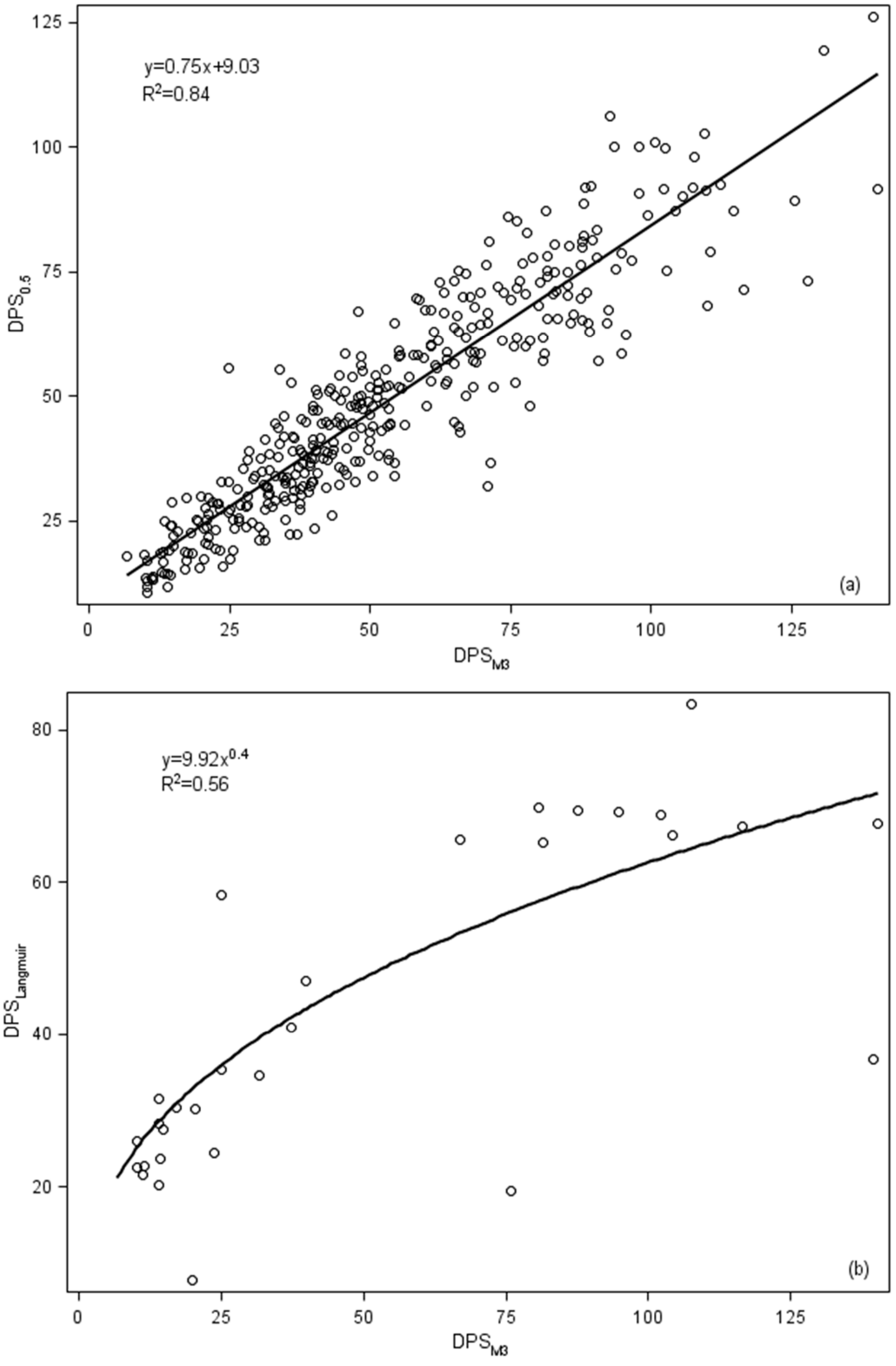

Figure 4.5 Relationship between (a) oxalate extractable DPS with alpha=0.5 ($DPS_{0.5}$) and linear conversion of Mehlich 3 P Saturation Ratio I to oxalate extractable DPS (DPS_{M3}) and (b) oxalate extractable DPS with calculated alpha ($DPS_{Langmuir}$) and DPS_{M3} for soils with $DPS_{0.5}<200$. All regressions significant at *$P<0.0001$*.

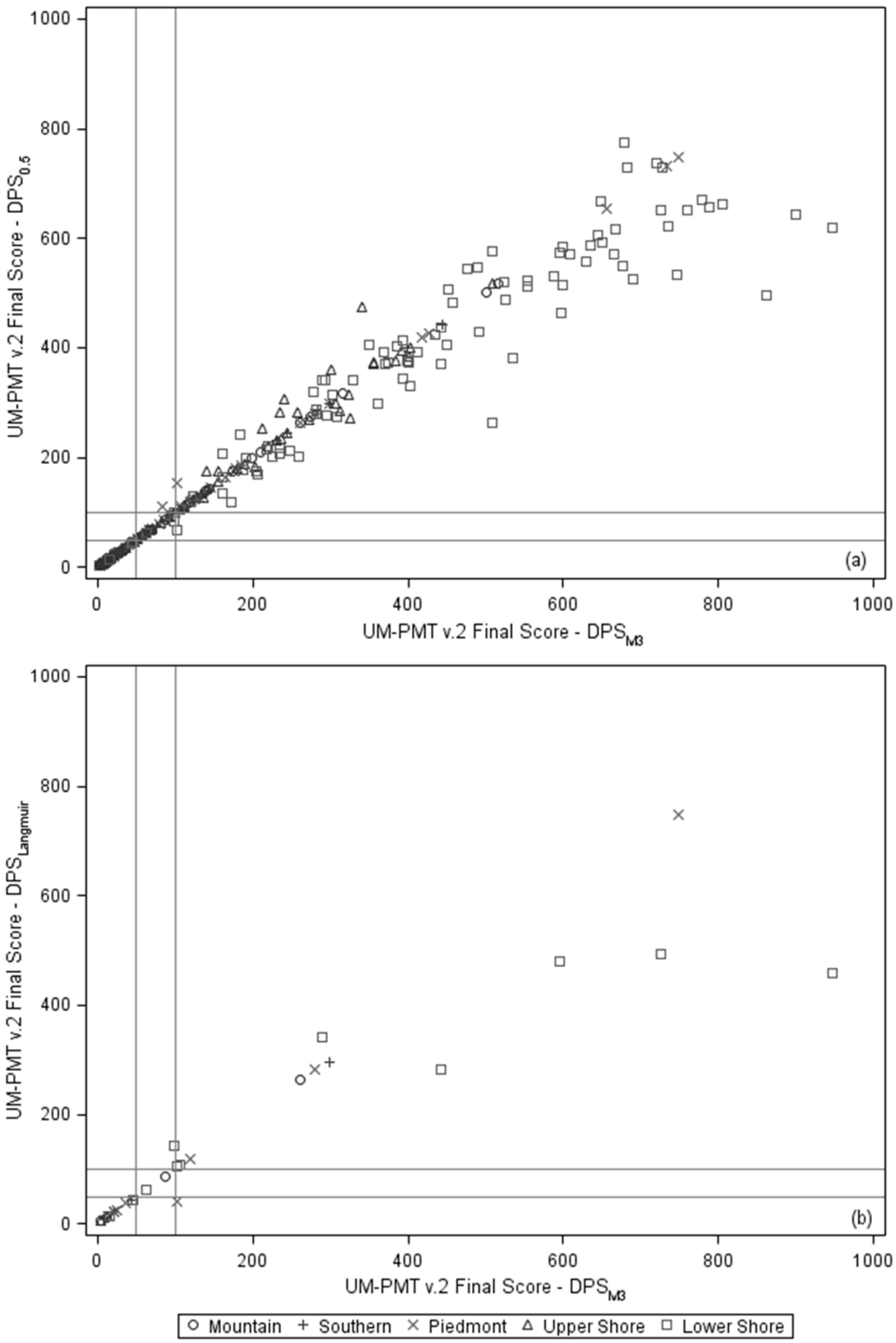

Figure 4.6 Comparison of final score for University of Maryland Phosphorus Management Tool v.2 (UM-PMT v.2) calculated using linear conversion of Mehlich 3 P Saturation Ratio I to oxalate extractable DPS (DPS$_{M3}$) and (a) oxalate extractable DPS with alpha=0.5 (DPS$_{0.5}$) and (b) oxalate extractable DPS with calculated alpha (DPS$_{Langmuir}$) by physiographic region in Maryland. Reference lines delineate interpretive categories for final score (Low<50, Medium 50-100, High>100).

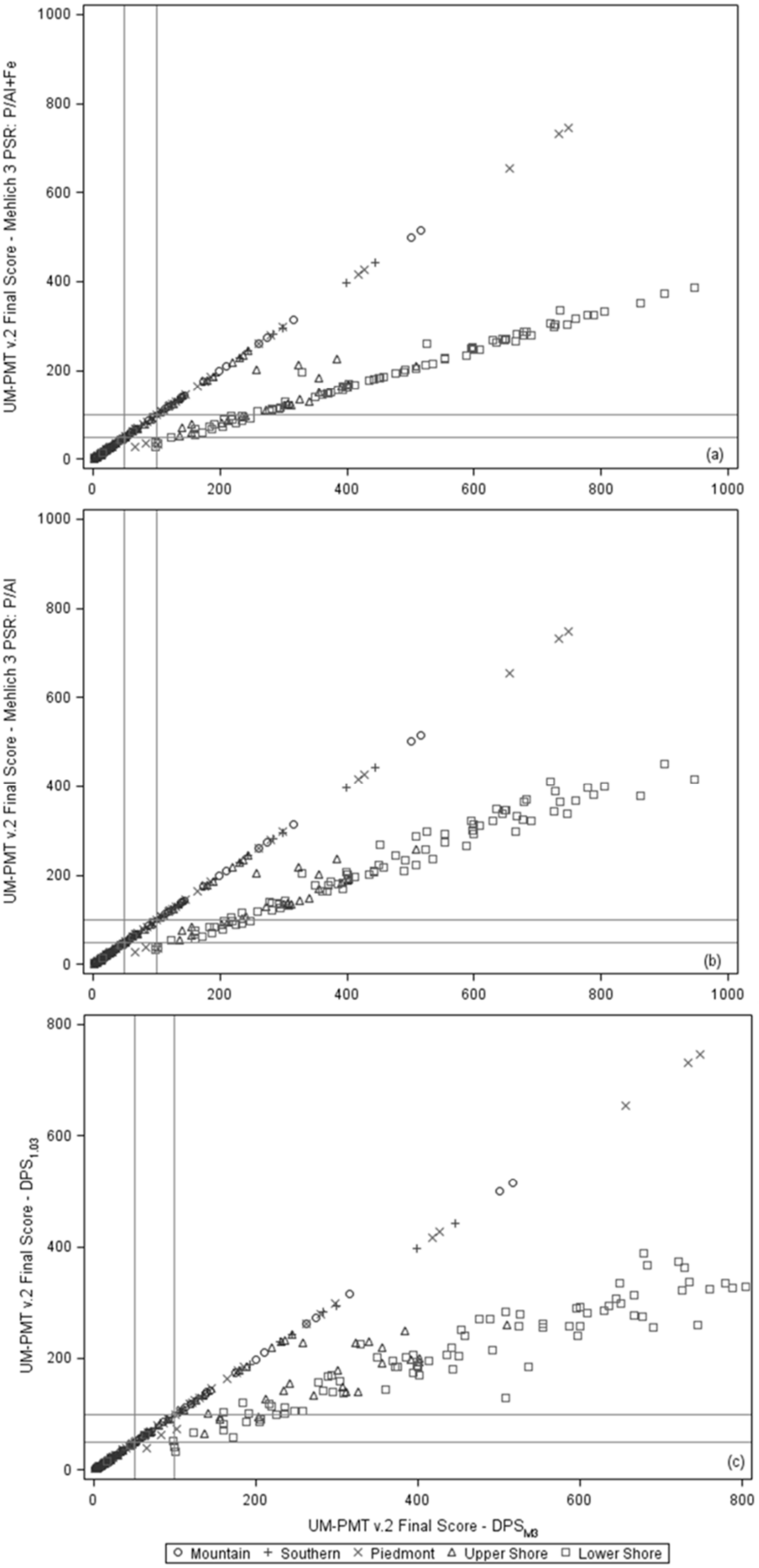
UM-PMT v.2 Final Score - Mehlich 3 PSR: P/Al+Fe
(a)
UM-PMT v.2 Final Score - Mehlich 3 PSR: P/Al
(b)
UM-PMT v.2 Final Score - $DPS_{1.03}$
(c)
UM-PMT v.2 Final Score - DPS_{M3}
0
200
400
600
800
1000
○ Mountain
+ Southern
× Piedmont
△ Upper Shore
□ Lower Shore

Figure 4.7 Comparison of final score for University of Maryland Phosphorus Management Tool v.2 (UM-PMT v.2) calculated using linear conversion of Mehlich 3 P Saturation Ratio I to oxalate extractable DPS (DPS_{M3})and (a) Mehlich 3 P Saturation Ratio I (M3PSR-I, [M3P]/[M3Al]+[M3Fe]), (B) Mehlich 3 P Saturation Ratio II (M3PSR-II, [M3P]/[M3Al]). and (c) oxalate extractable DPS with alpha=1.03 ($DPS_{1.03}$) by physiographic region in Maryland. Reference lines delineate interpretive categories for final score (Low<50, Medium 50-100, High>100).

Chapter 5. Comparison of Maryland Phosphorus Site Index and University of Maryland Phosphorus Management Tool Versions One and Two

5.1 Introduction

University of Maryland researchers modified the Maryland P Site Index (MD-PSI) to improve its ability to determine the relative risk of potential P loss from agricultural fields in Maryland. McGrath et al. (2013) changed the index from a multiplicative to component structure in order to make it more sensitive to different physiographic provinces with different P transport pathways. The index was renamed the University of Maryland Phosphorus Management Tool (UM-PMT). Additionally, the component structure allowed more precise targeting of management practices to specific P transport pathways, making the UM-PMT a better educational tool than the MD-PSI. Through evaluation of the UM-PMT by comparison to modeled P loss data, a third version of the MD-PSI was developed, UM-PMT Version 2 (UM-PMT v.2). This version was structured like the UM-PMT but included new input variables and management practices.

It is important to understand how sensitive the UM-PMT equation is to input variables before final implementation. One of the goals of modifying the original MD-PSI was to encourage adoption of better management practices. A sensitivity analysis provides feedback on how sensitive the UM-PMT is to management changes. This allows researchers to further refine the calculation to achieve the desired effect. Additionally, the sensitivity analysis provides information on how precise input measurements need to be in order to get accurate results from the UM-PMT. Some input variables may be expensive or time consuming to measure accurately. If the UM-PMT is not sensitive to the input variable, it may be acceptable to estimate that variable, potentially saving time for the end user (Bolster and Vadas, 2013). Finally, it is important to provide guidance information to UM-PMT end-users about how input factors and management choices will affect final score, as some management practices may be more effective at lowering final score than others. Therefore, the objectives of this study were to 1) investigate how the three versions of the Maryland P loss risk index compare to each other, 2) determine how sensitive the versions of UM-PMT are to the input variables, and 3) evaluate how sensitive the UM-PMT version are to changes in management.

5.2 Materials and Methods

5.2.1 Soil Sample Collection and Extraction

The dataset described in Chapter 2 was used for the current study. In brief, fields, located across Maryland (Table 2.1), were visited between 2011 and 2012. Researchers measured physical characteristics and recorded management practices required to calculate the MD-PSI, UM-PMT, and UM-PMT v.2 and collected soil samples to a depth of 20 cm during field visits. Samples were oven dried and ground to pass through a 2 mm sieve then P, Fe, and Al concentrations were determined using Mehlich 3 extraction (1:10 soil/0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.015M NH_4F + 0.13M HNO_3 + 0.0001M EDTA, (Mehlich, 1984)) and inductively coupled plasma atomic emission spectroscopy (ICP-AES). Field slope was measured using clinometers and distance to surface water was measured in field with a laser rangefinder. If water was not visible a soil survey or aerial imagery in Geographic Information System (GIS) software was used. Some of the fields visited had Mehlich 3 soil P concentrations below the threshold that would require the farmer to run the UM-PMT, equivalent to P Fertility Index Value (M3FIV) of 150. Since the Maryland PSI and UM-PMT were developed for use on fields above 150 FIV, a value of 150 FIV was substituted for the actual soil test where it was less than 150 FIV for the purposes of this study. In addition, a PSI or UM-PMT score is typically calculated if a P application is planned for the field of interest. Therefore, if no P application was planned in the current year, a manure application was simulated for the purpose of this evaluation, as described in Chapter 2, Section 2.1.

5.2.2 Phosphorus Index Equation Calculations

Researchers calculated the MD-PSI (Coale, 2008), UM-PMT (McGrath et al., 2013), and UM-PMT v.2 for each field. They then assigned each field to the appropriate interpretive category based on numerical final score. It should be noted that the MD-PSI has four interpretive categories while both versions of the UM-PMT have three. Finally, they estimated total P loss for each field using the Annual P Loss Estimator (APLE) model (Vadas, 2012b).

5.2.3 Sensitivity Analysis

Model sensitivity was determined by calculation of relative sensitivity. Relative sensitivity (S_r) was calculated for each continuous, numerical variable in UM-PMT and UM-PMT v.2 for each field in the dataset to determine which input variable would elicit the greatest change on each UM-PMT component output and final score when all variables are adjusted by the same percentage (Bolster and Vadas, 2013; Coleman and DeCoursey, 1976). A Sr value of one indicates an equal percentage of change in the output relative to the percentage of change in the input variable.

Relative sensitivity was calculated using Equation 5.1, where I represents the input variable, I_{min} represents the minimum value of I present in the dataset, and θ represents the output of interest. Both the component outputs and final score of the UM-PMT and UM-PMT v.2 were evaluated for their sensitivity to changing input variables.

Each input variable was modified by 10% ($\Delta I = 0.1 * I$), which was previously used by Bolster and Vadas (2013).

Equation 5.1 Relative Sensitivity (Sr) calculation

$$S_r = \frac{\partial\theta}{\partial I}\frac{I - I_{min}}{\theta}$$

$$\textit{where}$$

$$\frac{\partial\theta}{\partial I} \approx \frac{\theta_{I+\Delta I} - \theta_{I-\Delta}}{2\Delta I}$$

Thirteen management scenarios were developed in which each scenario would modify input variables, for each field in the dataset. Then, both versions of the UM-PMT were recalculated for all fields based on this input change. The scenarios represent management changes that could be implemented or other physical changes that could occur over time in Maryland (Table 5.1). Final score for UM-PMT and UM-PMT v.2 were calculated for all fields with each management scenario. Fields that were categorized as HIGH using the original UM-PMT and UM-PMT v.2 equations were isolated. The distribution of these fields into the interpretive categories was compared for each management scenario to determine if the management scenarios were able to lower final score and change interpretive category assignment.

5.3 Results and Discussion

5.3.1 Phosphorus Index Calculation Comparison

Of the three versions of the Maryland P risk index, the MD-PSI categorized most fields in the dataset into the LOW category while the UM-PMT categorized most fields into the HIGH category (Figure 5.1). The UM-PMT v.2 categorized fields similar to the MD-PSI, however more fields were categorized into the MEDIUM and HIGH categories than the MD-PSI. In general, the UM-PMT v.2 categorized fewer fields into higher categories than the UM-PMT but more fields into higher categories than the MD-PSI.

Mean proportion of final score for each P loss component was calculated for UM-PMT and UM-PMT v.2 but was not calculated for MD-PSI, as the MD-PSI was not separated into P loss components. The SUBSURFACE component comprised the greatest proportion of the final score for both versions of UM-PMT in the Lower Shore region of the state, while the PARTICULATE component comprised a greater proportion of the final score in the UM-PMT v.2 index than the UM-PMT for the remaining regions (Figure 5.2). Particulate-bound P is the dominant P loss pathway in most sloping regions, so it follows that PARTICULATE score should drive the final score of the P loss risk index in most regions of the state. In the Lower Shore region, where subsurface P loss is the dominant pathway, the subsurface pathway should comprise the greatest proportion of UM-PMT final score. The adjusted scaling factors for the components in the UM-PMT v.2 are likely responsible for this shift in proportion of final score, as the PARTICULATE pathway is weighted more heavily in the UM-PMT v.2 than the other components.

Final score for both UM-PMT and UM-PMT v.2 and total P loss estimated by the APLE model for each field were compared to determine how well the final score of the indices compare to total P loss (Figure 5.3). Since APLE only predicts P loss through surface pathways, fields with artificial drainage present were removed for the comparison, as subsurface P loss was assumed to be the dominant P loss pathway in those fields. Fields with RUSLE score greater than 15 and M3PFIV greater than 900 were also removed, as a RUSLE score greater than 15 and M3PFIV greater than 900 are very large and these fields would presumably have a high score for both indices. Final score for UM-PMT v.2 correlated better with estimated total P loss than UM-PMT however, there were a number of fields with low scores for both indices and relatively high estimated total P loss. This indicated the indices may need to be further scaled such that the maxima for interpretive categories correlate to specific total P loss values, as suggested by the USDA-NRCS 590 Nutrient Management Standard (NRCS, 2011). Final score for UM-PMT and UM-PMT v.2 were compared to determine if the indices assigned fields to similar interpretive categories. The largest percentage of fields (31%) were categorized as LOW for both versions of the UM-PMT (Table 5.2, Figure 5.4), followed by 28% of fields categorized as HIGH for both versions of the UM-PMT.

Results of the comparison of the three versions of the Maryland P risk index indicate differences do exist between the indices, as the calculation has been modified over time. The UM-PMT v.2 was an intermediate between MD-PSI and UM-PMT for distribution of fields into interpretive categories and tended to correlate better with estimated total P loss than UM-PMT. Further investigation into scaling UM-PMT v.2 interpretive categories based on estimated total P loss is recommended, as this may be necessary to ensure correct assignment of fields into interpretive categories.

5.3.2 Sensitivity Analysis

Relative sensitivity was determined for both versions of UM-PMT for sensitivity of component outputs and final scores to changes in input variables (Figures 5.5-5.6). MANURE DP component for both versions of the UM-PMT were sensitive to rate of manure application. The MANURE DP component of UM-PMT v.2 was most sensitive to WEP% of manure. This indicates it may be beneficial for producers to use the most accurate measure of WEP%, that is, to have manure WEP% determined from a manure sample analysis. Both versions of the SUBSURFACE component were sensitive to DPS and neither were very sensitive to the SD transport factor. However, the SUBSURFACE component of the UM-PMT v.2 was sensitive to management variable, indicating a change in management will likely affect the score of this component within the UM-PMT v.2. The PARTICULATE component of both versions of the UM-PMT were sensitive to the distance factor, indicating this variable should be accurately measured in the field. Finally, the SOIL DP component of the UM-PMT was most sensitive to DPS while the SOIL DP component of the UM-PMT v.2 was most sensitive to annual runoff, indicating an accurate method for annual runoff determination will need to be investigated before implementation of this version of the UM-PMT.

The sensitivity of the final score for both versions of the UM-PMT to each input variable was also investigated (Figures 5.7-5.8). The final scores for both versions were most sensitive to the distance factor within the PARTICULATE component. This was likely due to the PARTICULATE component comprising a large proportion of the final score for both UM-PMT versions. Final score for the UM-PMT v.2 was sensitive to management factor for the SUBSURFACE component, however was not as sensitive to management factors within the other P loss components. This indicated further modification to the management factors may be necessary to increase the sensitivity of the final score to these variables. The goal of the modifications to the UM-PMT was to increase the effect of management on the final score, in order to encourage producers to adopt better management practices.

Management scenarios were developed based on changes in management practices, such as adjustment to RUSLE score and use of management practices in UM-PMT v.2, to determine if implementation of these scenarios would re-categorize fields within the interpretive categories. Additionally, annual runoff is a new input variable to

UM-PMT v.2 and it was anticipated that this variable may be difficult for end-users to obtain. Therefore, the sensitivity of runoff as an input variable was also investigated (scenario M) to determine how accurately this variable should be measured. Overall, most scenarios did not change the interpretive category of the fields that scored HIGH with the original versions of the UM-PMT. Decreasing the C factor within the RUSLE calculation by 50% re-categorized 16 and 13 fields as MEDIUM, for UM-PMT and UM-PMT v.2, respectively (Table 5.3). The elimination of P amendment application re-categorized 9 fields as MEDIUM for the UM-PMT but did not re-categorize any fields for the UM-PMT v.2 (Table 5.3). It is possible that the scenarios resulted in numerical changes to final scores without changing interpretive category assignment. These results, similar to the sensitivity analysis, indicated further evaluation of the management factors within the UM-PMT v.2 to increase sensitivity of the final score to management variables.

Results of the sensitivity analyses indicate which input variables the indices are most sensitive to and which input variables can be measured or estimated. Each component of both versions of the UM-PMT varied in sensitivity to input variables. Both MANURE DP and SOIL DP components were sensitive to WEP% of manure and annual runoff, respectively, indicating these variables which are new to the UM-PMT v.2 should be measured accurately. Final score for both versions of the UM-PMT were sensitive to the distance factor within the PARTICULATE component, likely because the particulate component comprised a large proportion of the final score for both UM-PMT versions. Both sensitivity analyses indicated low sensitivity of the model to the management input variables and further evaluation of these factors should be considered, as the goal of UM-

PMT modification was to encourage implementation of better management practices by producers.

5.4 Conclusions

Of the three versions of the Maryland P Index, the MD-PSI was the least restrictive and the UM-PMT was the most restrictive. The SUBSURFACE component comprised the greatest proportion of final score for both version of the UM-PMT for fields in the Lower Shore region of Maryland while the PARTICULATE component comprised the greatest proportion of final score in other regions of the state. The final scores for UM-PMT v.2 correlated better with total P loss estimated by the APLE model than final scores for UM-PMT, however there were a number of fields with high estimated total P loss that received low UM-PMT or UM-PMT v.2 score, indicating further scaling of the final score for both versions of the UM-PMT may be necessary. The sensitivity analyses indicated the two versions of the UM-PMT are not highly sensitive to management factors within the calculations. While the two versions of the UM-PMT may result in numerically different final scores for the same field, the changes were not great enough to re-categorize fields into a different interpretive category. It is the assignment to interpretive categories that provide producers with management recommendations, therefore sensitivity of final score to management factors must be evaluated to allow for re-categorization of fields within interpretive categories as better management practices are adopted.

Evaluations of this nature are important to ensure correct assignment of fields to interpretive categories. Incorrect assignment of fields to interpretive categories could have major economic implications for farmers in Maryland through recommending unnecessary adoption of management practices. End-users of either version of the UM-

PMT with fields having a relatively high risk of P loss should experiment with a variety of management scenarios that would lower their field’s final score and decrease risk of P loss to surface water.

5.5 Tables

Table 5.1 List of management scenarios used in the sensitivity analysis

Scenarios
A. RUSLE score decreased by 10%
B. RUSLE score decreased by 20%
C. No P amendment applied to any field
D. Amendment rate applied at 0.5 current rate
E. All fields applying manure were assigned minimum score for amendment management factor ($AM_{r\text{-}v.2}$), 0.3 for solid manures and 0.05 for liquid manures
F. All fields with artificial drainage present were assigned minimum score for amendment management factor (AM), either 0.5 for ditch filter installation or 0.7 for use of irrigation of liquid manures
G. On all fields soil P concentration greater than 500, soil management factor is 0.8, representing credit for use of P-sorbing materials
H. All fields with manure application were assigned timing factor score of 0.8, representing manure applications were performed in the spring
I. All soil P concentrations increased by 25%
J. All soil P concentrations increased by 50%
K. RUSLE C factor decreased by 10%
L. RUSLE C factor decreased by 50%
M. Increase annual runoff by 10%

Table 5.2 Number of fields in the dataset (n=382) in each combination of UM-PMT and UM-PMT v.2 interpretive category

UM-PMT Category	UM-PMT v.2 Category	Number of fields	Percentage of Total
Low	High	0	0
Medium	High	9	2.4
High	High	108	28.3
Low	Medium	2	0.52
Medium	Medium	18	4.7
High	Medium	30	7.9
Low	Low	119	31.2
Medium	Low	71	18.6
High	Low	25	6.5

Table 5.3 Number of fields in each interpretive category for the University of Maryland Phosphorus Management Tool (UM-PMT) and UM-PMT Version 2 (UM-PMT v.2) for fields categorized as HIGH by the original version of the P risk index for each management scenarios.

	UM-PMT			**UM-PMT v.2**		
Scenario	**L**	**M**	**H**	**L**	**M**	**H**
Original Index	-	-	163	-	-	117
A	-	3	160	-	1	116
B	-	6	157	-	3	114
C	-	9	154	-	-	117
D	-	2	161	-	-	117
E	-	-	-	-	-	117
F	-	-	-	-	7	110
G	-	-	-	-	-	117
H	3	1	159	-	-	117
I	-	-	163	-	-	117
J	-	-	163	-	-	117
K	-	3	160	-	1	116
L	-	16	147	-	13	104
M	-	-	-	-	-	117

5.6 Figures

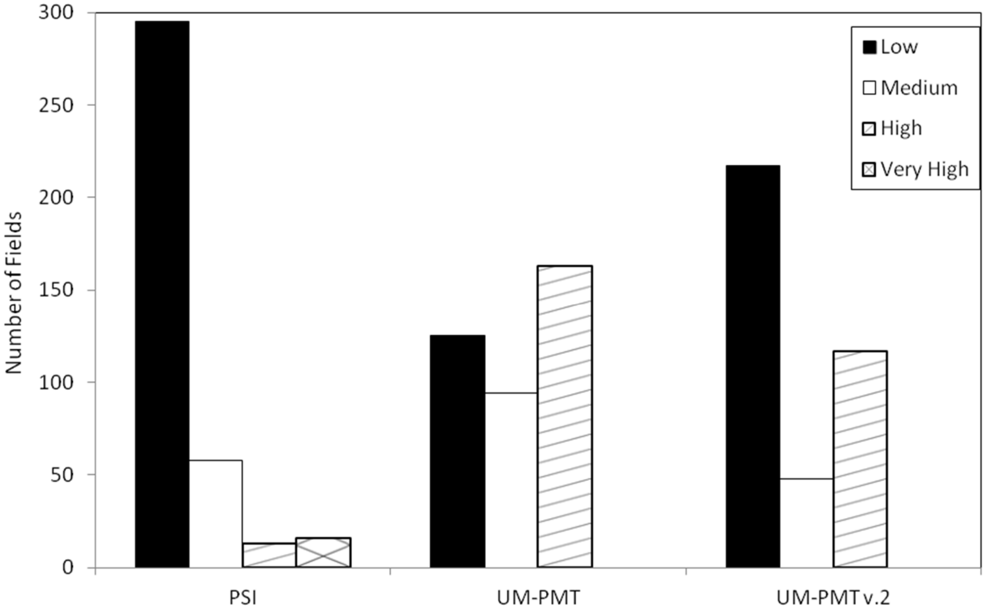

Figure 5.1 Number of fields in the dataset (n=380) with final scores within each interpretive category for the three versions of the Maryland P loss risk index, Maryland P Index (PSI), University of Maryland Phosphorus Management Tool (UM-PMT), and UM-PMT Version 2 (UM-PMT v.2).

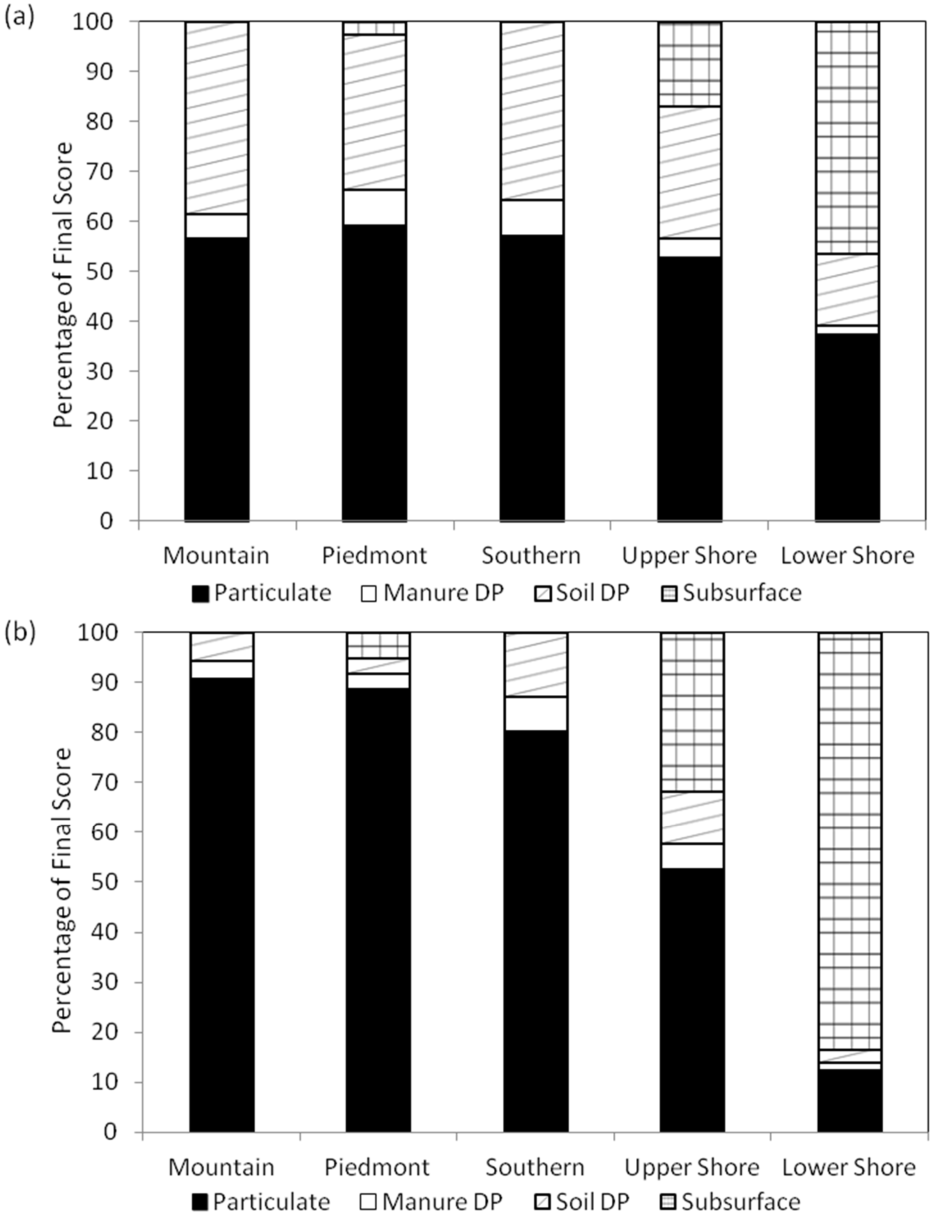

Figure 5.2 Mean proportion of final score by geographic region for each model component for (a) University of Maryland Phosphorus Management Tool (UM-PMT) and (b) UM-PMT Version 2 (UM-PMT v.2).

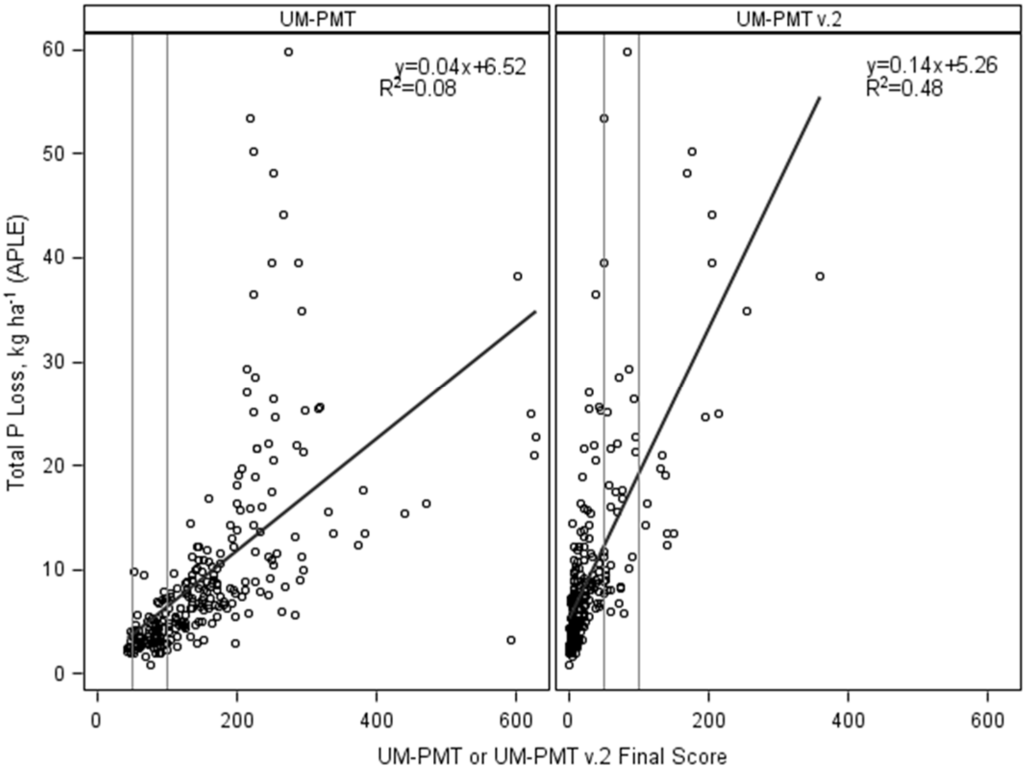

Figure 5.3 Final score for University of Maryland Phosphorus Management Tool (UM-PMT) and UM-PMT Version 2 (UM-PMT v.2) versus total P loss in kg ha^{-1} estimated by the APLE model for fields in the dataset without artificial drainage, RUSLE score >15 and Mehlich 3 P Fertility Index Value > 900 removed (n=250). Reference lines delineate interpretive categories for final score (Low<50, Medium 50-100, High>100) and all equation significant at *P<0.0001*.

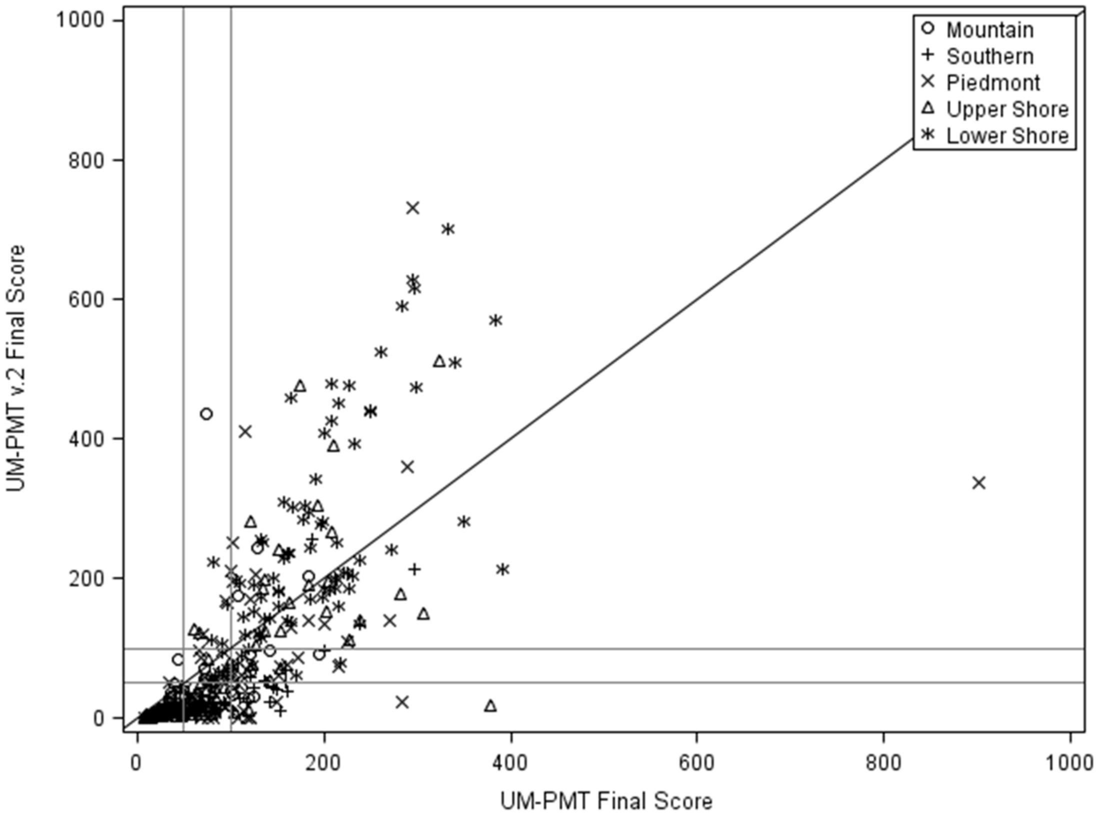

Figure 5.4 Final scores for University of Maryland Phosphorus Management Tool (UM-PMT) and UM-PMT Version 2 (UM-PMT v.2) for all fields in the dataset by physiographic region (n=382). Reference lines delineate interpretive categories for final score (Low<50, Medium 50-100, High>100).

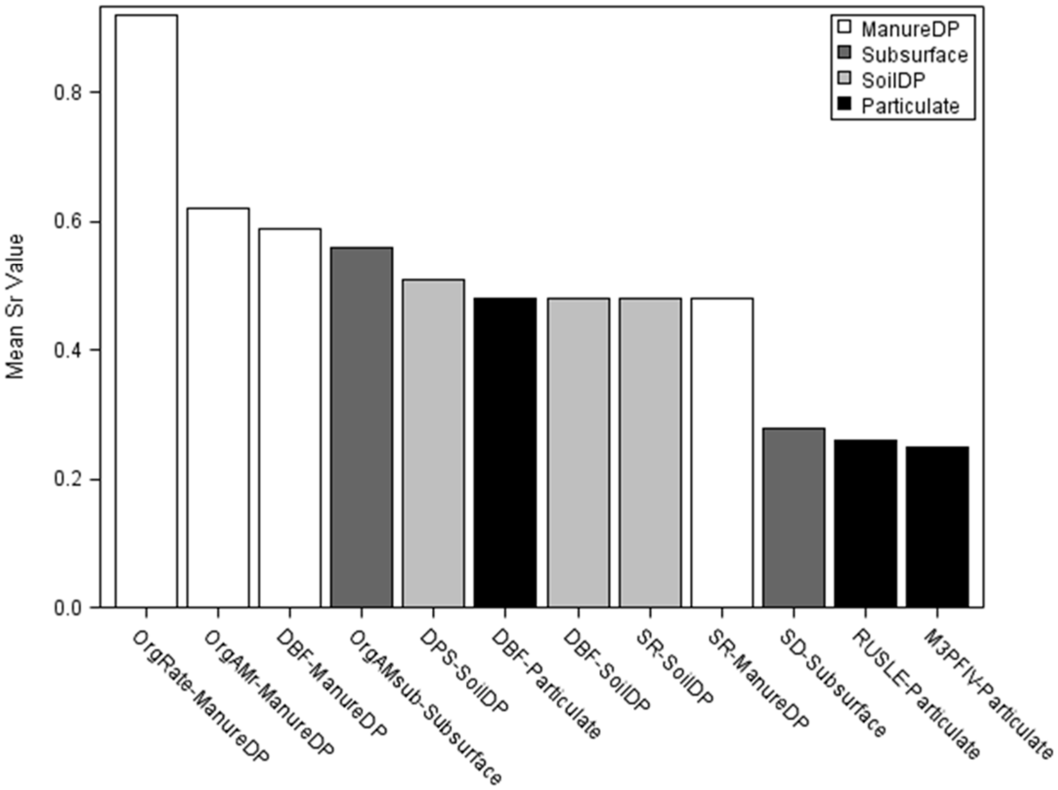

Figure 5.5 Mean relative sensitivity (Sr) for each input variable on the respective P loss component in the University of Maryland Phosphorus Management Tool (UM-PMT) by P loss component.

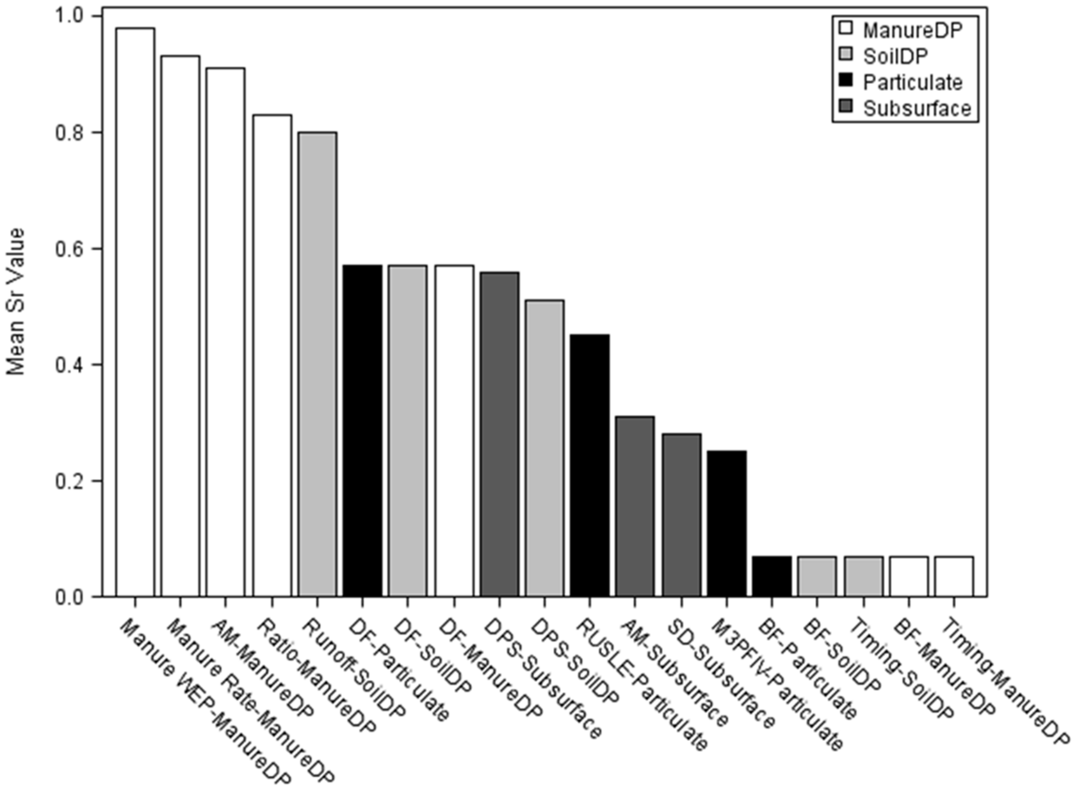

Figure 5.6 Mean relative sensitivity (Sr) for each input variable on the respective P loss component in the University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2) by P loss component.

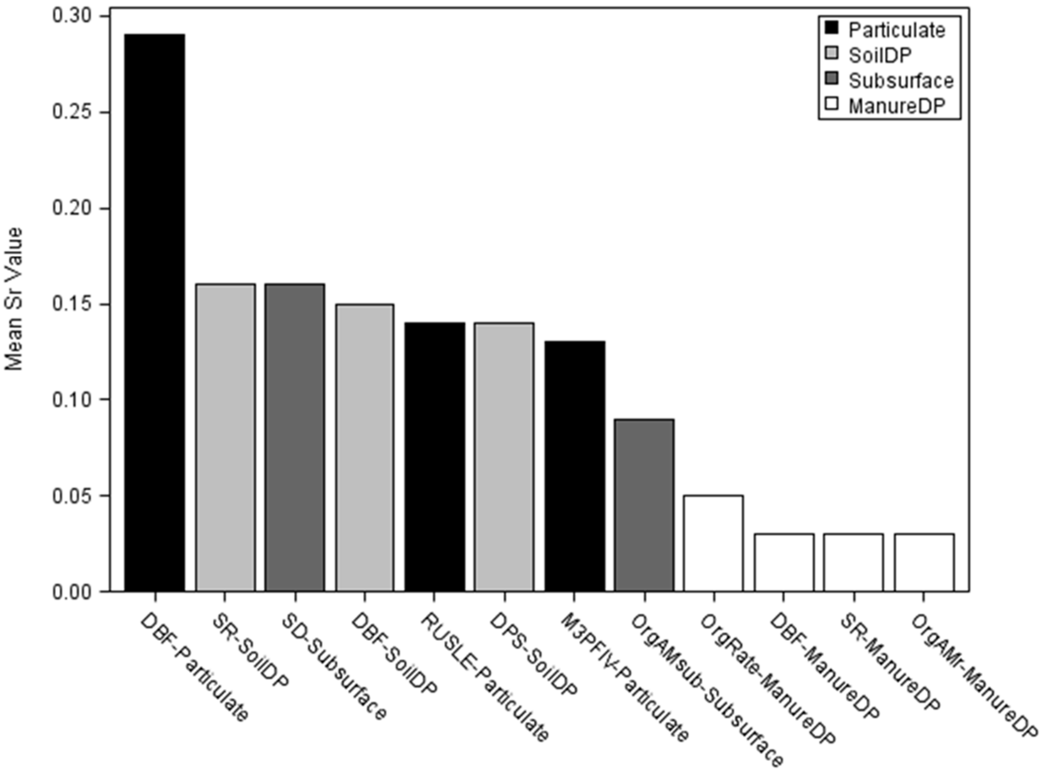

Figure 5.7 Mean relative sensitivity (Sr) for each input variable on the final score of the University of Maryland Phosphorus Management Tool (UM-PMT) by P loss component.

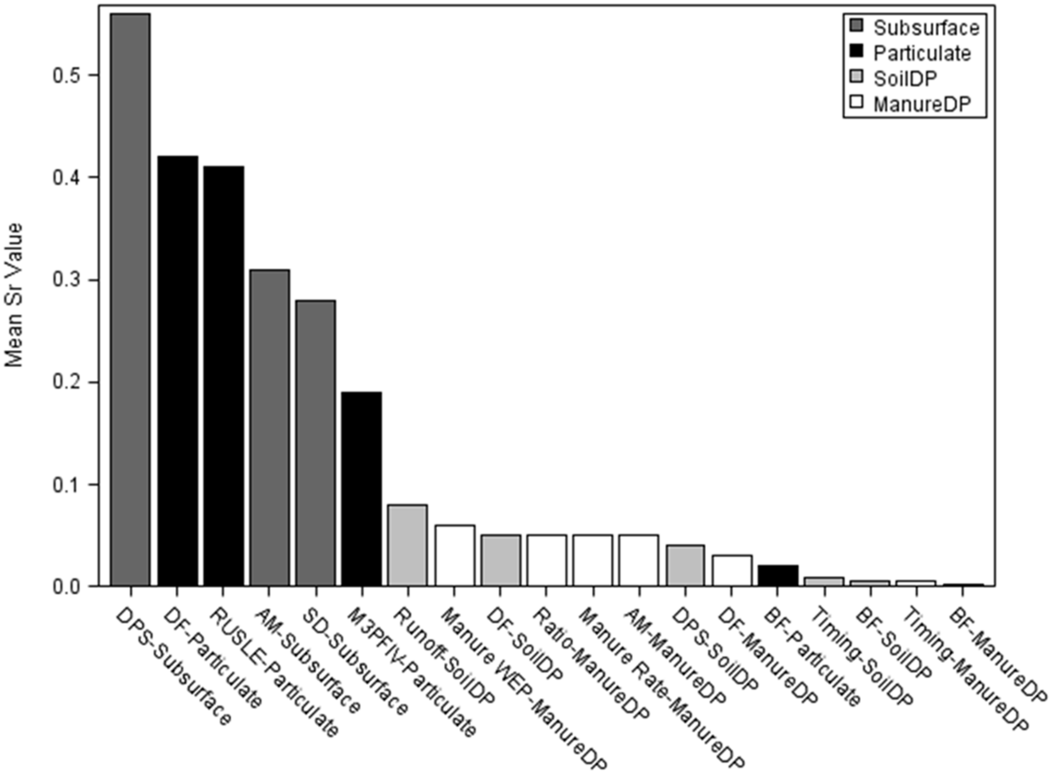

Figure 5.8 Mean relative sensitivity (Sr) for each input variable on the final score of the University of Maryland Phosphorus Management Tool Version 2 (UM-PMT v.2) by P loss component.

Chapter 6. Appendix

6.1 Coding for creation of simulated dataset

```
*simulation code;
DATA SIMULATION;
DO SUB=1 TO 15000;
      COUNTY=FLOOR(1+(24-1)*RANUNI(1));
IF County IN (19,9,22,23) THEN Region = 'Lower Shore';
If County IN (1,11,21) THEN Region = 'Mountain';
IF County IN (3,6,7,10,12,13,15) THEN Region = 'Piedmont';
IF County IN (2,4,6,8,16,18) THEN Region = 'Southern';
IF County IN (5,14,17,20) THEN Region = 'Upper Shore';

      SOILDEPTH=1;
      M3P = ROUND(19+(700-1)*RANUNI(1),1);
      M3AL=ROUND(1+(1698-1)*RANUNI(1),1);
      M3FE=ROUND(1+(673-1)*RANUNI(1),1);
      RILL='MODERATE';

*soil type assignment;
IF COUNTY=1 THEN NUM=FLOOR(64+(152-64)*RANUNI(1));
ELSE IF COUNTY=2 THEN NUM=FLOOR(152+(239-152)*RANUNI(1));
ELSE IF COUNTY=3 THEN NUM=FLOOR(239+(364-239)*RANUNI(1));
ELSE IF COUNTY=4 THEN NUM=FLOOR(364+(405-364)*RANUNI(1));
ELSE IF COUNTY=5 THEN NUM=FLOOR(405+(441-405)*RANUNI(1));
ELSE IF COUNTY=6 THEN NUM=FLOOR(441+(536-441)*RANUNI(1));
ELSE IF COUNTY=7 THEN NUM=FLOOR(536+(639-536)*RANUNI(1));
ELSE IF COUNTY=8 THEN NUM=FLOOR(639+(687-639)*RANUNI(1));
ELSE IF COUNTY=9 THEN NUM=FLOOR(687+(716-687)*RANUNI(1));
ELSE IF COUNTY=10 THEN NUM=FLOOR(716+(853-716)*RANUNI(1));
ELSE IF COUNTY=11 THEN NUM=FLOOR(853+(884-853)*RANUNI(1));
ELSE IF COUNTY=12 THEN NUM=FLOOR(884+(941-884)*RANUNI(1));
ELSE IF COUNTY=13 THEN NUM=FLOOR(941+(1016-941)*RANUNI(1));
ELSE IF COUNTY=14 THEN NUM=FLOOR(1016+(1069-1016)*RANUNI(1));
ELSE IF COUNTY=15 THEN NUM=FLOOR(1069+(1136-1069)*RANUNI(1));
ELSE IF COUNTY=16 THEN NUM=FLOOR(1136+(1211-1136)*RANUNI(1));
ELSE IF COUNTY=17 THEN NUM=FLOOR(1211+(1243-1211)*RANUNI(1));
ELSE IF COUNTY=18 THEN NUM=FLOOR(1243+(1309-1243)*RANUNI(1));
ELSE IF COUNTY=19 THEN NUM=FLOOR(1309+(1340-1309)*RANUNI(1));
ELSE IF COUNTY=20 THEN NUM=FLOOR(1340+(1371-1340)*RANUNI(1));
ELSE IF COUNTY=21 THEN NUM=FLOOR(1371+(1488-1371)*RANUNI(1));
ELSE IF COUNTY=22 THEN NUM=FLOOR(1488+(1534-1488)*RANUNI(1));
ELSE IF COUNTY=23 THEN NUM=FLOOR(1534+(1577-1534)*RANUNI(1));
ELSE NUM=100000;

*county % assignment;
IF COUNTY=1 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=2 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=3 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=4 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=5 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=6 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=7 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
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ELSE IF COUNTY=8 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=9 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=10 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=11 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=12 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=13 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=14 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=15 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=16 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=17 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=18 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=19 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=20 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=21 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=22 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF COUNTY=23 THEN PERCENT=ROUND(0+(100-1)*RANUNI(1),5);

*SLOPE LENGTH;
IF COUNTY=1 THEN SLOPE_LENGTH=ROUND(47+(600-47)*RANUNI(1),10);
ELSE IF COUNTY=2 THEN SLOPE_LENGTH=ROUND(50+(215-50)*RANUNI(1),10);
ELSE IF COUNTY=3 THEN SLOPE_LENGTH=ROUND(122+(350-122)*RANUNI(1),10);
ELSE IF COUNTY=4 AND PERCENT<65 THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=4 AND PERCENT>=65 THEN SLOPE_LENGTH=ROUND(120+(550-
120)*RANUNI(1),10);
ELSE IF COUNTY=5 AND PERCENT>=85 THEN SLOPE_LENGTH=ROUND(180+(500-
180)*RANUNI(1),10);
ELSE IF COUNTY=5 AND PERCENT<85 THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=6 THEN SLOPE_LENGTH=ROUND(225+(600-225)*RANUNI(1),10);
ELSE IF COUNTY=7 THEN SLOPE_LENGTH=ROUND(0+(500-0)*RANUNI(1),10);
ELSE IF COUNTY=8 THEN SLOPE_LENGTH=ROUND(139+(435-139)*RANUNI(1),10);
ELSE IF COUNTY=9 AND PERCENT<=80 THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=9 AND PERCENT>80 THEN SLOPE_LENGTH=ROUND(150+(315-
150)*RANUNI(1),10);
ELSE IF COUNTY=10 THEN SLOPE_LENGTH=ROUND(85+(360-85)*RANUNI(1),10);
ELSE IF COUNTY=11 THEN SLOPE_LENGTH=ROUND(0+(487-0)*RANUNI(1),10);
ELSE IF COUNTY=12 THEN SLOPE_LENGTH=ROUND(100+(372-100)*RANUNI(1),10);
ELSE IF COUNTY=13 THEN SLOPE_LENGTH=ROUND(115+(588-115)*RANUNI(1),10);
ELSE IF COUNTY=14 AND PERCENT<=50 THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=14 AND PERCENT>50 THEN SLOPE_LENGTH=ROUND(215+(400-
251)*RANUNI(1),10);
ELSE IF COUNTY=15 THEN SLOPE_LENGTH=ROUND(90+(330-90)*RANUNI(1),10);
ELSE IF COUNTY=16 THEN SLOPE_LENGTH=ROUND(0+(325-0)*RANUNI(1),10);
ELSE IF COUNTY=17 THEN SLOPE_LENGTH=ROUND(0+(600-0)*RANUNI(1),10);
ELSE IF COUNTY=18 THEN SLOPE_LENGTH=ROUND(50+(300-50)*RANUNI(1),1);
ELSE IF COUNTY IN (19,22,23) THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=20 AND PERCENT>=50 THEN SLOPE_LENGTH=0;
ELSE IF COUNTY=20 AND PERCENT<50 THEN SLOPE_LENGTH=ROUND(100+(385-
100)*RANUNI(1),10);
ELSE IF COUNTY=21 THEN SLOPE_LENGTH=ROUND(0+(423-0)*RANUNI(1),1);

*region % assignment;
IF REGION='Lower Shore' THEN PERCENT_REG=ROUND(0+(100-1)*RANUNI(1),5);
ELSE IF REGION='Piedmont' THEN PERCENT_REG=ROUND(0+(100-
1)*RANUNI(1),5);
ELSE IF REGION='Upper Shore' THEN PERCENT_REG=ROUND(0+(100-
1)*RANUNI(1),5);
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ELSE IF REGION='Mountain' THEN PERCENT_REG=ROUND(0+(100-
1)*RANUNI(1),5);
ELSE IF REGION='Southern' THEN PERCENT_REG=ROUND(0+(100-
1)*RANUNI(1),5);

*annual rainfall for state;
ANNUAL_RAIN_IN = ROUND(9+(48-1)*RANUNI(1),1);

*R factor;
IF COUNTY=1 OR COUNTY=11 THEN R=115;
ELSE IF COUNTY IN (2,14,16,17) THEN R=185;
ELSE IF COUNTY IN(3,13) THEN R=175;
ELSE IF COUNTY IN (4,5,8,20) THEN R=190;
ELSE IF COUNTY=6 THEN R=160;
ELSE IF COUNTY IN (7,12) THEN R=180;
ELSE IF COUNTY IN (9,18,22) THEN R=195;
ELSE IF COUNTY=10 THEN R=155;
ELSE IF COUNTY=15 THEN R=170;
ELSE IF COUNTY IN (19,23) THEN R=200;
ELSE IF COUNTY=21 THEN R=125;

*priority of receiving water body;
IF COUNTY=1 AND PERCENT<=30 THEN PRIORITY=4;
ELSE IF COUNTY=1 AND PERCENT>3 THEN PRIORITY=5;
ELSE IF COUNTY=2 AND PERCENT>=25 THEN PRIORITY=2;
ELSE IF COUNTY=2 AND PERCENT<25 THEN PRIORITY=4;
ELSE IF COUNTY=3 AND PERCENT<=10 THEN PRIORITY=5;
ELSE IF COUNTY=3 AND PERCENT>10 AND PERCENT<30 THEN PRIORITY=4;
ELSE IF COUNTY=3 AND PERCENT>=30 THEN PRIORITY=2;
ELSE IF COUNTY=4 THEN PRIORITY=5;
ELSE IF COUNTY=5 AND PERCENT<=25 THEN PRIORITY=1;
ELSE IF COUNTY=5 AND PERCENT>25 AND PERCENT<35 THEN PRIORITY=2;
ELSE IF COUNTY=5 AND PERCENT>=35 THEN PRIORITY=4;
ELSE IF COUNTY=6 THEN PRIORITY=4;
ELSE IF COUNTY=7 AND PERCENT<30 THEN PRIORITY=5;
ELSE IF COUNTY=7 AND PERCENT>=30 THEN PRIORITY=4;
ELSE IF COUNTY=8 AND PERCENT>35 THEN PRIORITY=5;
ELSE IF COUNTY=8 AND PERCENT<=35 THEN PRIORITY=4;
ELSE IF COUNTY=9 AND PERCENT<=20 THEN PRIORITY=5;
ELSE IF COUNTY=9 AND PERCENT>20 AND PERCENT<55 THEN PRIORITY=4;
ELSE IF COUNTY=9 AND PERCENT>=55 THEN PRIORITY=2;
ELSE IF COUNTY=10 AND PERCENT<=50 THEN PRIORITY=4;
ELSE IF COUNTY=10 AND PERCENT>50 THEN PRIORITY=5;
ELSE IF COUNTY=11 THEN PRIORITY=5;
ELSE IF COUNTY=12 AND PERCENT<=55 THEN PRIORITY=5;
ELSE IF COUNTY=12 AND PERCENT>55 THEN PRIORITY=2;
ELSE IF COUNTY=13 AND PERCENT<=50 THEN PRIORITY=1;
ELSE IF COUNTY=13 AND PERCENT>50 THEN PRIORITY=4;
ELSE IF COUNTY=14 AND PERCENT<=40 THEN PRIORITY=2;
ELSE IF COUNTY=14 AND PERCENT>40 THEN PRIORITY=4;
ELSE IF COUNTY=15 AND PERCENT>=25 THEN PRIORITY=5;
ELSE IF COUNTY=15 AND PERCENT<25 THEN PRIORITY=4;
ELSE IF COUNTY=16 THEN PRIORITY=2;
ELSE IF COUNTY=17 AND PERCENT<=30 THEN PRIORITY=2;
ELSE IF COUNTY=17 AND PERCENT>30 AND PERCENT<45 THEN PRIORITY=5;
ELSE IF COUNTY=17 AND PERCENT>=45 THEN PRIORITY=4;
ELSE IF COUNTY=18 THEN PRIORITY=4;
```

```
ELSE IF COUNTY=19 AND PERCENT<=40 THEN PRIORITY=2;
ELSE IF COUNTY=19 AND PERCENT>40 THEN PRIORITY=4;
ELSE IF COUNTY=20 AND PERCENT<=5 THEN PRIORITY=1;
ELSE IF COUNTY=20 AND PERCENT>5 AND PERCENT<=40 THEN PRIORITY=2;
ELSE IF COUNTY=20 AND PERCENT>40 AND PERCENT<=85 THEN PRIORITY=4;
ELSE IF COUNTY=20 AND PERCENT>85 THEN PRIORITY=5;
ELSE IF COUNTY=21 AND PERCENT<=15 THEN PRIORITY=1;
ELSE IF COUNTY=21 AND PERCENT>15 AND PERCENT<=30 THEN PRIORITY=2;
ELSE IF COUNTY=21 AND PERCENT>30 AND PERCENT<=45 THEN PRIORITY=4;
ELSE IF COUNTY=21 AND PERCENT>45 THEN PRIORITY=5;
ELSE IF COUNTY=22 AND PERCENT<=20 THEN PRIORITY=5;
ELSE IF COUNTY=22 AND PERCENT>20 THEN PRIORITY=2;
ELSE IF COUNTY=23 AND PERCENT<=20 THEN PRIORITY=2;
ELSE IF COUNTY=23 AND PERCENT>20 AND PERCENT<=75 THEN PRIORITY=4;
ELSE IF COUNTY=23 AND PERCENT>75 THEN PRIORITY=5;

*presence of drainage;
IF REGION = 'Lower Shore' THEN AD='present';
ELSE IF REGION='Mountain' OR REGION='Southern' OR REGION='Piedmont'
THEN AD='absent';
ELSE IF REGION='Upper Shore' AND PERCENT_REG<30 THEN AD='present';
ELSE IF REGION='Upper Shore' AND PERCENT_REG>30 THEN AD='absent';

*buffers;
IF REGION='Lower Shore' AND PERCENT_REG>=70 THEN
BUFF_VEG_TYPE='Vegetated';
ELSE IF REGION='Lower Shore' AND PERCENT_REG<70 THEN BUFF_VEG_TYPE='No
Buffer';
ELSE IF REGION='Mountain' OR REGION='Upper Shore' OR REGION='Piedmont'
OR REGION='Southern' THEN BUFF_VEG_TYPE='Vegetated';

IF BUFF_VEG_TYPE='No Buffer' THEN BUFFER=0;
ELSE IF REGION='Lower Shore' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG<=85 THEN BUFFER=ROUND(1+(25-1)*RANUNI(1),1);
ELSE IF REGION='Lower Shore' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>85 THEN BUFFER=ROUND(35+(85-35)*RANUNI(1),1);
ELSE IF REGION='Mountain' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG<=5 THEN BUFFER=ROUND(1+(25-1)*RANUNI(1),1);
ELSE IF REGION='Mountain' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>5 THEN BUFFER=ROUND(35+(85-35)*RANUNI(1),1);
ELSE IF REGION='Piedmont' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG<=15 THEN BUFFER=ROUND(1+(25-1)*RANUNI(1),1);
ELSE IF REGION='Piedmont' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>50 AND PERCENT_REG<=65 THEN BUFFER=ROUND(35+(50-
35)*RANUNI(1),1);
ELSE IF REGION='Piedmont' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>65 THEN BUFFER=65;
ELSE IF REGION='Southern' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG<=75 THEN BUFFER=ROUND(1+(50-1)*RANUNI(1),1);
ELSE IF REGION='Southern' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>75 THEN BUFFER=65;
ELSE IF REGION='Upper Shore' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG<=15 THEN BUFFER=ROUND(1+(25-1)*RANUNI(1),1);
ELSE IF REGION='Upper Shore' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>15 AND PERCENT_REG<=40 THEN BUFFER=ROUND(25+(50-
25)*RANUNI(1),1);
```

```
ELSE IF REGION='Upper Shore' AND BUFF_VEG_TYPE='Vegetated' AND
PERCENT_REG>40 THEN BUFFER=65;

*no P application zone;
NO_P2=ROUND(1+(2-1)*RANUNI(1),1);
IF NO_P2=1 THEN NO_P='>25';
ELSE IF NO_P2=2 THEN NO_P='<25';

*distance to surface water;
IF REGION='Lower Shore' AND PERCENT_REG<=95 THEN D=ROUND(0+(100-
0)*RANUNI(1),1);
ELSE IF REGION='Lower Shore' AND PERCENT_REG>95 THEN D=ROUND(100+(600-
100)*RANUNI(1),1);
ELSE IF REGION='Mountain' AND PERCENT_REG<=5 THEN D=ROUND(0+(100-
0)*RANUNI(1),1);
ELSE IF REGION='Mountain' AND PERCENT_REG>5 THEN D=ROUND(100+(600-
100)*RANUNI(1),1);
ELSE IF REGION='Piedmont' OR REGION='Southern' AND PERCENT_REG<=15 THEN
D=ROUND(0+(100-0)*RANUNI(1),1);
ELSE IF REGION='Piedmont' OR REGION='Southern' AND PERCENT_REG>15 THEN
D=ROUND(100+(600-100)*RANUNI(1),1);
ELSE IF REGION='Upper Shore' AND PERCENT_REG<=30 THEN D=ROUND(0+(100-
0)*RANUNI(1),1);
ELSE IF REGION='Upper Shore' AND PERCENT_REG>30 THEN D=ROUND(100+(600-
100)*RANUNI(1),1);

*crop rotation;
*1=corn-wheat-soybeans-cover crop, 2=corn-soybeans,3=continuous corn,
4=continuous corn-cover crop,5=silage-cover crop (for silage),
6=silage-cover crop;
IF COUNTY IN (1,21,11,10,14,6) THEN ROTATION=FLOOR(1+(7-1)*RANUNI(1));
ELSE ROTATION=FLOOR(1+(5-1)*RANUNI(1));

*TILLAGE FOR CURRENT CROP - CORN FOR ALL;
*1=NO TILL, 2=REDUCED, 3=CONVENTIONAL;
TILL=FLOOR(1+(4-1)*RANUNI(1));

*TILLAGE FOR PREVIOUS CROP;
*1=NO TILL, 2=REDUCED, 3=CONVENTIONAL;
IF ROTATION=3 THEN PREVTILL=0;
ELSE PREVTILL=FLOOR(1+(4-1)*RANUNI(1));

*C factor;
IF ROTATION=1 AND TILL=1 AND PREVTILL=1 THEN C=0.01;
ELSE IF ROTATION=1 AND TILL=1 AND PREVTILL=2 THEN C=0.03;
ELSE IF ROTATION=1 AND TILL=1 AND PREVTILL=3 THEN C=0.05;
ELSE IF ROTATION=1 AND TILL=2 AND PREVTILL=1 THEN C=0.05;
ELSE IF ROTATION=1 AND TILL=2 AND PREVTILL=2 THEN C=0.065;
ELSE IF ROTATION=1 AND TILL=2 AND PREVTILL=3 THEN C=0.085;
ELSE IF ROTATION=1 AND TILL=3 AND PREVTILL=1 THEN C=0.08;
ELSE IF ROTATION=1 AND TILL=3 AND PREVTILL=2 THEN C=0.09;
ELSE IF ROTATION=1 AND TILL=3 AND PREVTILL=3 THEN C=0.11;
ELSE IF ROTATION=2 AND TILL=1 AND PREVTILL=1 THEN C=0.04;
ELSE IF ROTATION=2 AND TILL=1 AND PREVTILL=2 THEN C=0.1;
ELSE IF ROTATION=2 AND TILL=1 AND PREVTILL=3 THEN C=0.16;
ELSE IF ROTATION=2 AND TILL=2 AND PREVTILL=1 THEN C=0.1;
ELSE IF ROTATION=2 AND TILL=2 AND PREVTILL=2 THEN C=0.14;
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ELSE IF ROTATION=2 AND TILL=2 AND PREVTILL=3 THEN C=0.19;
ELSE IF ROTATION=2 AND TILL=3 AND PREVTILL=1 THEN C=0.12;
ELSE IF ROTATION=2 AND TILL=3 AND PREVTILL=2 THEN C=0.16;
ELSE IF ROTATION=2 AND TILL=3 AND PREVTILL=3 THEN C=0.2;
ELSE IF ROTATION=3 AND TILL=1 THEN C=0.02;
ELSE IF ROTATION=3 AND TILL=2 THEN C=0.08;
ELSE IF ROTATION=3 AND TILL=3 THEN C=0.16;
ELSE IF ROTATION=4 AND TILL=1 AND PREVTILL=1 THEN C=0.01;
ELSE IF ROTATION=4 AND TILL=1 AND PREVTILL=2 THEN C=0.04;
ELSE IF ROTATION=4 AND TILL=1 AND PREVTILL=3 THEN C=0.11;
ELSE IF ROTATION=4 AND TILL=2 AND PREVTILL=1 THEN C=0.08;
ELSE IF ROTATION=4 AND TILL=2 AND PREVTILL=2 THEN C=0.1;
ELSE IF ROTATION=4 AND TILL=2 AND PREVTILL=3 THEN C=0.16;
ELSE IF ROTATION=4 AND TILL=3 AND PREVTILL=1 THEN C=0.13;
ELSE IF ROTATION=4 AND TILL=3 AND PREVTILL=2 THEN C=0.14;
ELSE IF ROTATION=4 AND TILL=3 AND PREVTILL=3 THEN C=0.18;
ELSE IF ROTATION=5 AND TILL=1 AND PREVTILL=1 THEN C=0.09;
ELSE IF ROTATION=5 AND TILL=1 AND PREVTILL=2 THEN C=0.13;
ELSE IF ROTATION=5 AND TILL=1 AND PREVTILL=3 THEN C=0.16;
ELSE IF ROTATION=5 AND TILL=2 AND PREVTILL=1 THEN C=0.19;
ELSE IF ROTATION=5 AND TILL=2 AND PREVTILL=2 THEN C=0.21;
ELSE IF ROTATION=5 AND TILL=2 AND PREVTILL=3 THEN C=0.23;
ELSE IF ROTATION=5 AND TILL=3 AND PREVTILL=1 THEN C=0.22;
ELSE IF ROTATION=5 AND TILL=3 AND PREVTILL=2 THEN C=0.23;
ELSE IF ROTATION=5 AND TILL=3 AND PREVTILL=3 THEN C=0.25;
ELSE IF ROTATION=6 AND TILL=1 AND PREVTILL=1 THEN C=0.1;
ELSE IF ROTATION=6 AND TILL=1 AND PREVTILL=2 THEN C=0.15;
ELSE IF ROTATION=6 AND TILL=1 AND PREVTILL=3 THEN C=0.18;
ELSE IF ROTATION=6 AND TILL=2 AND PREVTILL=1 THEN C=0.23;
ELSE IF ROTATION=6 AND TILL=2 AND PREVTILL=2 THEN C=0.25;
ELSE IF ROTATION=6 AND TILL=2 AND PREVTILL=3 THEN C=0.26;
ELSE IF ROTATION=6 AND TILL=3 AND PREVTILL=1 THEN C=0.26;
ELSE IF ROTATION=6 AND TILL=3 AND PREVTILL=2 THEN C=0.27;
ELSE IF ROTATION=6 AND TILL=3 AND PREVTILL=3 THEN C=0.29;
*IF REGION='Lower Shore' OR REGION='Piedmont' OR REGION='Upper Shore'
THEN C=ROUND(0.02+(1-0.02)*RANUNI(1),0.01);
*ELSE IF REGION='Southern' OR REGION='Mountain' THEN C=ROUND(0.02+(0.5-
0.02)*RANUNI(1),0.01);

*P factor;
IF AD='present' THEN P=0.6;
ELSE IF COUNTY IN (5,9) THEN P=ROUND(0.92+(1-0.92)*RANUNI(1),0.01);
ELSE IF COUNTY=11 THEN P=ROUND(0.85+(1-0.85)*RANUNI(1),0.01);
ELSE P=1;

*manure type;
IF ROTATION IN (5,6) THEN ORGTYPE2=2;
ELSE ORGTYPE2=FLOOR(1+(6-1)*RANUNI(1));
IF ORGTYPE2=1 THEN ORGTYPE='Biosolids';
ELSE IF ORGTYPE2=2 THEN ORGTYPE='Dairy';
ELSE IF ORGTYPE2=3 THEN ORGTYPE='Poultry';
ELSE IF ORGTYPE2=4 THEN ORGTYPE='Swine';
ELSE IF ORGTYPE2=5 THEN ORGTYPE='Beef';

*manure units;
IF ORGTYPE='Biosolids' OR ORGTYPE='Beef' OR ORGTYPE='Poultry' THEN
MANURE_UNITS='tons/acre';
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ELSE MANURE_UNITS='gal/acre';

*P2O5 applied in #/ac;
MANURE_P2O5=ROUND(0+(400-0)*RANUNI(1),1);

*manure total P in mg/kg;
IF ORGTYPE='Beef' THEN SOLID_MANURE_TP_MGKG=ROUND(3100+(8300-
3100)*RANUNI(1),1);
ELSE IF ORGTYPE='Dairy' THEN LIQUID_MANURE_TP_MGKG=ROUND(1800+(17300-
1800)*RANUNI(1),1);
ELSE IF ORGTYPE='Poultry' THEN SOLID_MANURE_TP_MGKG=ROUND(9400+(26200-
9400)*RANUNI(1),1);
ELSE IF ORGTYPE='Swine' THEN LIQUID_MANURE_TP_MGKG=ROUND(5000+(45000-
5000)*RANUNI(1),1);
ELSE IF ORGTYPE='Biosolids' THEN SOLID_MANURE_TP_MGKG=ROUND(500+(4100-
500)*RANUNI(1),1);

*converts total P into #P2O5/ton for solids or #P2O5/1000 gal for
liquids;
*DIVISION BY 0.246 IS RATIO OF P TO P2O5;
SOLID_MANURE_TP_LBS=ROUND(SOLID_MANURE_TP_MGKG*0.002,1)/0.246;
LIQUID_MANURE_TP_LBS=ROUND(LIQUID_MANURE_TP_MGKG*0.00835,1)/0.246;

IF MANURE_UNITS = "tons/acre" THEN LIQUID_MANURE_TP_MGKG = 0;
ELSE SOLID_MANURE_TP_MGKG=0;
IF MANURE_UNITS= "tons/acre" THEN LIQUID_MANURE_TP_LBS = 0;
ELSE SOLID_MANURE_TP_LBS=0;

*GENERATE PERCENTAGE OF TP THAT IS WEP;
IF ORGTYPE='Beef' THEN WEP_PERCENTAGE=ROUND(4+(93-4)*RANUNI(1),1);
ELSE IF ORGTYPE='Dairy' THEN WEP_PERCENTAGE=ROUND(25+(84-
25)*RANUNI(1),1);
ELSE IF ORGTYPE='Poultry' THEN WEP_PERCENTAGE=ROUND(7.5+(33-
7.5)*RANUNI(1),1);
ELSE IF ORGTYPE='Swine' THEN WEP_PERCENTAGE=ROUND(13+(90-
13)*RANUNI(1),1);
ELSE IF ORGTYPE='Biosolids' THEN WEP_PERCENTAGE=ROUND(0.03+(24-
0.03)*RANUNI(1),1);

*CONVERT MG/KG OF TOTAL P TO G/KG FOR WEP100 EQUATION IN UM-PMT;
LIQUID_MANURE_TP_GKG=LIQUID_MANURE_TP_MGKG/1000;
SOLID_MANURE_TP_GKG=SOLID_MANURE_TP_MGKG/1000;
IF MANURE_UNITS= "tons/acre" THEN LIQUID_MANURE_TP_GKG = 0;
ELSE SOLID_MANURE_TP_GKG=0;

*GENERATE WEP AS PERCENT OF TP, IN G/KG;
IF ORGTYPE='Beef' THEN
MANURE_WEP=(WEP_PERCENTAGE*SOLID_MANURE_TP_GKG)/100;
ELSE IF ORGTYPE='Dairy' THEN
MANURE_WEP=(WEP_PERCENTAGE*LIQUID_MANURE_TP_GKG)/100;
ELSE IF ORGTYPE='Poultry' THEN
MANURE_WEP=(WEP_PERCENTAGE*SOLID_MANURE_TP_GKG)/100;
ELSE IF ORGTYPE='Swine' THEN
MANURE_WEP=(WEP_PERCENTAGE*LIQUID_MANURE_TP_GKG)/100;
ELSE IF ORGTYPE='Biosolids' THEN
MANURE_WEP=(WEP_PERCENTAGE*SOLID_MANURE_TP_GKG)/100;
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*RATE OF MANURE APPLED, TON/AC FOR SOLIDS, GAL/AC FOR LIQUID;
IF MANURE_UNITS='tons/acre' THEN
MANURE_RATE=ROUND(MANURE_P2O5/SOLID_MANURE_TP_LBS,0.1);
ELSE MANURE_RATE=ROUND((MANURE_P2O5/LIQUID_MANURE_TP_LBS)*1000,0.1);

MEAS_WEP='Yes';

*solids;
IF ORGTYPE='Beef' THEN MANURE_SOLIDS=ROUND(19+(73-19)*RANUNI(1),1);
ELSE IF ORGTYPE='Dairy' THEN MANURE_SOLIDS=ROUND(0.5+(40-
0.5)*RANUNI(1),1);
ELSE IF ORGTYPE='Poultry' THEN MANURE_SOLIDS=ROUND(56+(80-
56)*RANUNI(1),1);
ELSE IF ORGTYPE='Swine' THEN MANURE_SOLIDS=ROUND(0.5+(34-
0.5)*RANUNI(1),1);
ELSE IF ORGTYPE='Biosolids' THEN MANURE_SOLIDS=ROUND(6+(93-
6)*RANUNI(1),1);

*method of application;
IF TILL=1 THEN ORGPMETHOD2=1;
ELSE ORGPMETHOD2=ROUND(2+(4-2)*RANUNI(1),1);

IF ORGPMETHOD2=3 THEN ORGPMETHOD='Injected';
ELSE IF ORGPMETHOD2=1 THEN ORGPMETHOD='Surface';
ELSE IF ORGPMETHOD2=2 THEN ORGPMETHOD='<5';
ELSE IF ORGPMETHOD2=4 THEN ORGPMETHOD='>5';

*timing of application, IF statement based on new regulations;
IF ORGPMETHOD='Surface' OR ORGPMETHOD='Injected' THEN ORGPAPPTIMING2=1;
ELSE ORGPAPPTIMING2=ROUND(1+(2-1)*RANUNI(1),1);

IF ORGPAPPTIMING2=1 THEN ORGPAPPTIMING='Summer';
ELSE IF ORGPAPPTIMING2=2 THEN ORGPAPPTIMING='Winter';

*manure incorporation;
IF ORGPMETHOD='<5' THEN MANURE_INCORP=0.8;
ELSE IF ORGPMETHOD IN ('>5','Injected','Surface') THEN
MANURE_INCORP=0.1;

*fertilizer;
INP2O5=0;
INORGPMETHOD='';
INORGPAPPTIMING='';
FERT_INCORP='';
*INP2O5=ROUND(1+(60-1)*RANUNI(1),1);
*INORGPMETHOD2=ROUND(1+(4-1)*RANUNI(1),1);
*IF INORGPMETHOD2=1 THEN INORGPMETHOD='Surface';
*ELSE IF INORGPMETHOD2=2 THEN INORGPMETHOD='<5';
*ELSE IF INORGPMETHOD2=3 THEN INORGPMETHOD='>5';

*IF INORGPMETHOD='Surface' THEN INORGPAPPTIMING2=1;
*ELSE INORGPAPPTIMING2=ROUND(1+(2-1)*RANUNI(1),1);
*IF INORGPAPPTIMING2=1 THEN INORGPAPPTIMING='Summer';
*ELSE IF INORGPAPPTIMING2=2 THEN INORGPAPPTIMING='Winter';

*IF INORGPMETHOD='<5' THEN FERT_INCORP=0.8;
*ELSE IF INORGPMETHOD IN ('>5','Surface') THEN FERT_INCORP=0.1;
```

```
OUTPUT;
END;
RUN;

*Keep variables that are necessary;
DATA SIMULATION;
SET SIMULATION;
KEEP COUNTY REGION NUM SOILDEPTH M3P M3AL M3FE RILL ANNUAL_RAIN_IN
ANNUAL_RUNOFF_MM R SLOPE_LENGTH PRIORITY ROTATION TILL PREVTILL C P AD
BUFF_VEG_TYPE BUFFER NO_P D ORGTYPE MANURE_UNITS MANURE_P2O5
SOLID_MANURE_TP_MGKG LIQUID_MANURE_TP_MGKG SOLID_MANURE_TP_LBS
LIQUID_MANURE_TP_LBS MEAS_WEP MANURE_WEP MANURE_SOLIDS MANURE_RATE
ORGPMETHOD ORGPAPPTIMING MANURE_INCORP MANURE_WEPG WEP_PERCENTAGE
INP2O5 INORGPMETHOD INORGPAPPTIMING FERT_INCORP;
RUN;
*Importing SSURGO soils data from computer;
PROC IMPORT OUT= WORK.SOILa
            DATAFILE= "C:\Users\Nicole Fiorellino\Google
Drive\Ph.D\Research\APLE\state soil database.xls"
            DBMS=EXCEL REPLACE;
     RANGE="final$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
*Modifying imported soils data;
DATA SOILa;
set soila;
IF AREASYMBOL='MD001' THEN COUNTY=1;
ELSE IF AREASYMBOL='MD003' THEN COUNTY=2;
ELSE IF AREASYMBOL='MD005' THEN COUNTY=3;
ELSE IF AREASYMBOL='MD009' THEN COUNTY=4;
ELSE IF AREASYMBOL='MD011' THEN COUNTY=5;
ELSE IF AREASYMBOL='MD013' THEN COUNTY=6;
ELSE IF AREASYMBOL='MD015' THEN COUNTY=7;
ELSE IF AREASYMBOL='MD017' THEN COUNTY=8;
ELSE IF AREASYMBOL='MD019' THEN COUNTY=9;
ELSE IF AREASYMBOL='MD021' THEN COUNTY=10;
ELSE IF AREASYMBOL='MD023' THEN COUNTY=11;
ELSE IF AREASYMBOL='MD027' THEN COUNTY=12;
ELSE IF AREASYMBOL='MD029' THEN COUNTY=14;
ELSE IF AREASYMBOL='MD031' THEN COUNTY=15;
ELSE IF AREASYMBOL='MD033' THEN COUNTY=16;
ELSE IF AREASYMBOL='MD035' THEN COUNTY=17;
ELSE IF AREASYMBOL='MD037' THEN COUNTY=18;
ELSE IF AREASYMBOL='MD039' THEN COUNTY=19;
ELSE IF AREASYMBOL='MD041' THEN COUNTY=20;
ELSE IF AREASYMBOL='MD043' THEN COUNTY=21;
ELSE IF AREASYMBOL='MD045' THEN COUNTY=22;
ELSE IF AREASYMBOL='MD047' THEN COUNTY=23;
ELSE IF AREASYMBOL='MD600' THEN COUNTY=13;
ELSE COUNTY=0;
```

```
SLOPE=ROUND(SLOPE_L+(SLOPE_H-SLOPE_L)*RANUNI(1),1);
IF SLOPE>15 THEN DELETE;
IF NICCDCD>4 THEN DELETE;
IF NICCDCD='' THEN DELETE;
IF SANDTOTAL1=0 THEN DELETE;
IF DRCLASSDCD='' THEN DELETE;
RUN;
*Create dataset to number soil types;
DATA SOILB;
DO NUM=1 TO 1576;
OUTPUT;
END;
RUN;
*Sort imported soils data to merge with numbers;
PROC SORT DATA=SOILa;
BY COUNTY;
RUN;
*Merge soils data with numbers;
DATA SOIL;
SET SOILa;
SET SOILB;
KEEP NUM musym_1 muname wtdepannmi drclassdcd hydgrpdcd niccdcd
sandtotal1 silttotal1 claytotal1 om_r ksat_r kwfact county slope_l
slope_r slope_h slope;
RUN;
DATA SOIL;
SET SOIL;
*PERMEABILITY;
KSAT=KSAT_R*0.1417323;
IF KSAT>2 AND KSAT<6 THEN PERMEABILITY='MODERATELY RAPID';
IF KSAT>=0.2 AND KSAT<0.6 THEN PERMEABILITY='MODERATELY SLOW';
ELSE IF KSAT>=20 THEN PERMEABILITY='VERY RAPID';
ELSE IF KSAT<20 AND KSAT>=2 THEN PERMEABILITY='RAPID';
ELSE IF KSAT<2 AND KSAT>=0.6 THEN PERMEABILITY='MODERATE';
ELSE IF KSAT<0.2 AND KSAT>=0.06 THEN PERMEABILITY='SLOW';
ELSE IF KSAT<0.06 THEN PERMEABILITY='VERY SLOW';

*K FACTOR;
K=(KWFACT+1)-1;
IF KWFACT='' AND SANDTOTAL1>CLAYTOTAL1+SILTTOTAL1 THEN
K=ROUND((0.05+(0.2-0.05)*RANUNI(1)),0.01);
ELSE IF KWFACT='' AND SILTTOTAL1>CLAYTOTAL1+SANDTOTAL1 THEN
K=ROUND((0.4+(0.65-0.4)*RANUNI(1)),0.01);
ELSE IF KWFACT='' AND CLAYTOTAL1>SANDTOTAL1+SILTTOTAL1 THEN
K=ROUND((0.25+(0.4-0.25)*RANUNI(1)),0.01);

*HSG;
HSG=HYDGRPDCD;
IF HYDGRPDCD='' AND CLAYTOTAL1<10 AND SANDTOTAL1>75 THEN HSG='A';
ELSE IF HYDGRPDCD='' AND CLAYTOTAL1<10 AND CLAYTOTAL1<20 AND
SANDTOTAL1>50 AND SANDTOTAL1<75 THEN HSG='B';
ELSE IF HYDGRPDCD='' AND CLAYTOTAL1>20 AND CLAYTOTAL1<30 AND
SANDTOTAL1<50 THEN HSG='C';
ELSE IF HYDGRPDCD='' AND CLAYTOTAL1>30 AND SANDTOTAL1<50 THEN HSG='D';
ELSE IF HYDGRPDCD='A/D' THEN HSG='D';
ELSE IF HYDGRPDCD='B/D' THEN HSG='D';
ELSE IF HYDGRPDCD='C/D' THEN HSG='D';
```

```
*leaching potential;
IF OM_R<=4 AND OM_R>=1 THEN LEACH='Medium';
ELSE IF OM_R>4 THEN LEACH='Low';
ELSE IF OM_R<1 THEN LEACH='High';

DEPTH=WTDEPANNMI;
SOIL_DRAIN=DRCLASSDCD;
CLAY=CLAYTOTAL1;
SAND=SANDTOTAL1;
SILT=SILTTOTAL1;
OM=OM_R;
KEEP MUSYM MUNAME DEPTH SOIL_DRAIN LEACH CLAY SAND SILT OM COUNTY NUM
KSAT PERMEABILITY K HSG SLOPE;
RUN;
*sort soils data for merge;
PROC SORT DATA=SOIL;
BY NUM;
RUN;

*Sort simulation data for merge;
PROC SORT DATA=SIMULATION;
BY NUM;
RUN;
*merge code;
DATA APLESIM;
MERGE SOIL SIMULATION;
BY NUM;
RUN;
*remove any blank data entries;
DATA APLESIM;
SET APLESIM;
IF SOILDEPTH='' THEN DELETE;
RUN;
```

6.2 Variables used in the simulated dataset, including source of variable, minimum value, maximum value, and type of variable.

Variable	Definition	Type	Min	Max	How it was coded	Reference
Musym	Soil type symbol	Categorical			From the state soils data	USGS
Muname	Soil type name	Categorical			From the state soils data	USGS
County	County name	Categorical	23 options	Maryland counties	Uniform distribution, randomly assigned	-
Permeability	Soil permeability, category (µm/sec converted to in/hr)	Categorical	4 options	moderate, moderately slow, rapid, very rapid	Based on definition of permeability class	Old P Index factsheet
HSG	Hydrologic soil group	Categorical	4 options	A,B,C,D	From the state soils data OR calculated based on soil texture	USGS; NRCS Part 630 Hydrology National Engineering Handbook: HSG
Leach	Leaching potential	Categorical	3 options	high, medium, low	From soils data, or calculated if not in dataset	USGS
Soil_drain	Soil drainage class	Categorical	7 options	excessively, moderately well, poorly, somewhat excessively, somewhat poorly, very poorly, well	From soils data	USGS
Region	Physiographic region	Categorical	5 options	Regions	Based on county	-

Variable	Definition	Type	Min	Max	How it was coded	Reference
Rill	Rill severity, for MD-PSI	Categorical	1 option	moderate	-	-
Priority	Priority of receiving waterbody	Categorical	4 options	1,2,4,5	Randomly assigned by county with uniform distribution, based on distribution from collected dataset	Required for MD-PSI, MD-PSI guidance documents
AD	Present of drains, for calculating SUBSURFACE component of PMT	Categorical	2 options	absent, present	Randomly assigned by region with uniform distribution, based on distribution from collected dataset	-
Buff_veg_ type	Type of vegetation present in buffers	Categorical	2 options	no buffer, vegetated	Randomly assigned by region with uniform distribution, based on distribution from collected dataset	-
No_P	No P application zone, required for MD-PSI	Categorical	2 options	>25, <25	Randomly assigned with uniform distribution	-
Orgtype	Type of manure applied	Categorical	5 options	Beef, Dairy, Poultry, Biosolids, Swine	Randomly assigned with uniform distribution	-
Manure_units	Tons/ac or gal/ac, to distinguish manures	Categorical	2 options	gal/ac, tons/ac	Assigned based on manure type	-

Variable	Definition	Type	Min	Max	How it was coded	Reference
Meas_WEP	Has WEP been measured?	Categorical	1 option	yes	Variable for PSI code to calculate PSC from WEP versus use of book value	-
OrgPmethod	Method of organic P application	Categorical	4 options	<5, >5, injected, surface	Randomly assigned with uniform distribution	-
OrgPApp Timing	Timing of organic P application	Categorical	2 options	summer, winter	If manure was surface applied or injected, timing=summer, else randomly assigned with uniform distribution	-
Manure_ incorp	Manure incorporation, needed for APLE	Categorical	2 options	0.1, 0.8	-	APLE 2.3 User Manual
InorgP Method	Method for application of inorganic P	Categorical			Randomly assigned with a uniform distribution	-
InorgPApp Timing	Timing of inorganic P application	Categorical			Randomly assigned with a uniform distribution	-
Fert_incorp	Fertilizer incorporation	Categorical			-	APLE 2.3 User Manual
Num	Assigned number to each soil type for merging datasets	Numerical	64	1576	Assigned to each soil type	-

Variable	Definition	Type	Min	Max	How it was coded	Reference
Ksat	Saturated hydraulic conductivity, µm/sec	Numerical	0.283	85.03	From state soil data	USGS
K	K factor for RUSLE	Numerical	0.02	0.49	From the state soils data	USGS
Depth	Depth to seasonal high water table	Numerical	0	168	From soils data	USGS
Clay	% clay in soil	Numerical	0	36.3	From soils data	USGS
Sand	% sand in soil	Numerical	5.9	99.4	From soils data	USGS
Silt	% silt in soil	Numerical	0.6	79	From soils data	USGS
Om	Organic matter	Numerical	0.02	16.75	From soils data	USGS
M3P	Mehlich 3 P	Numerical	19	718	Uniform distribution, randomly assigned	-
M3Al	Mehlich 3 Al	Numerical	1	1698	Uniform distribution, randomly assigned	-
M3Fe	Mehlich 3 Fe	Numerical	1	673	Uniform distribution, randomly assigned	-
Annual_rain_in	Annual rainfall, inches	Numerical	9	56	Uniform distribution, randomly assigned – range set by PSI dataset	
Annual_runoff_mm	Annual runoff, mm	Numerical			Calculated from annual precipitation using the curve number (CN) method, not best estimate but better than random	NRCS-SCS 1972

Variable	Definition	Type	Min	Max	How it was coded	Reference
R	R factor for RUSLE	Numerical	115	200	Numerically assigned by county, each county has a specific R value	MD-PSI supporting documents
Slope	Field slope	Numerical	0	15	From soils data, randomly assigned value between low and high associated with each soil type	-
Slope_length	Slope length	Numerical	0	600	Randomly assigned by county with uniform distribution, based on distribution from collected dataset	-
C	C factor for RUSLE	Numerical	0.01	0.29	Randomly assigned by region with uniform distribution, based on distribution from collected dataset	-
P	P factor for RUSLE	Numerical	0.6	1	Randomly assigned by county with uniform distribution, based on distribution from collected dataset	-
Buffer	Length of buffer	Numerical	0	85	Randomly assigned by region with uniform distribution, based on distribution from collected dataset	-

Variable	Definition	Type	Min	Max	How it was coded	Reference
D	Distance to surface water	Numerical	0	600	Randomly assigned by region with uniform distribution, based on distribution from collected dataset AND additional distances added to more uniform distribution of categories	Additional distances based on distribution of categories, collected dataset did not measure distance to water beyond 300 ft
Manure_ P2O5	Amount of P2O5 applied, #/acre	Numerical	0	400	Randomly assigned with uniform distribution	Typical management practices in the region
WEP_Percentage_mean	Mean percentage of TP that is WEP	Numerical	5	60	One mean value was determined from literature reference and assigned to each manure type	Kleinman et al. 2005 SSSAJ. Survey of WEP in livestock manure
Manure_ WEP	WEP content of manure in g/kg (for calculation of PSC in MD-PSI)	Numerical	1.45	9.2	One mean value was determined from literature reference and assigned to each manure type	Kleinman et al. 2005 SSSAJ. Survey of WEP in livestock manure

6.3 *Soils descriptions for all sampled soils*

County	Soil Abbreviation	Series	Description	Texture
Allegany	CfA	Cavode silt loam	Fine, mixed, active, mesic Aeric Endoaquults	Silt loam
Allegany	GcD	Gilpin channery silt loam	Fine-loamy, mixed, active, mesic Typic Hapludults	Silt loam
Allegany	LtC	Litz silt loam	Loamy-skeletal, mixed, active, mesic Ruptic-Ultic Dystrudepts	Silt loam
Allegany	OnD	Opequon silty clay loam	Clayey, mixed, active, mesic Lithic Hapludalfs	Silty clay loam
Allegany	WrB	Wharton silt loam	Fine-loamy, mixed, active, mesic Aquic Hapludults	Silt loam
Anne Arundel	CoC	Collington Wist complex	Fine-loamy, mixed, active, mesic Typic Hapludults	Fine sandy loam
Anne Arundel	MaB	Marr Dodon complex	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Fine sandy loam
Anne Arundel	MDE	Marr and Dodon soils	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Fine sandy loam
Baltimore	GdB	Glenelg loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	Loam
Baltimore	GeC	Glenelg channery loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	Loam
Baltimore	KeB	Keyport silt loam	Fine, mixed, semiactive, mesic Aquic Hapludults	Silt loam
Baltimore	SaB	Sassafras sandy loam	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Baltimore	SbA	Sassafras loam	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Loam

County	Soil Abbreviation	Series	Description	Texture
Calvert	DeA	Dodon-Crosiadore complex	Fine-silty, mixed, active, mesic Aquic Hapludults	Sandy loam
Calvert	DmC	Dodon-Marr complex	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Calvert	HaB	Hambrook fine sandy loam	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Fine sandy loam
Calvert	HeA	Hambrook-Woodstown complex	Fine-loamy, mixed, active, mesic Aquic Hapludults	Fine sandy loam
Calvert	IwC	Ingleside-Woodstown complex	Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults	Loamy sand
Calvert	MaB	Marr Dodon complex	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Fine sandy loam
Calvert	RsB	Rosedale fine sand	Loamy, siliceous, semiactive, mesic Arenic Hapludults	Sand
Calvert	WdA	Woodstown sandy loam	Fine-loamy, mixed, active, mesic Aquic Hapludults	Sandy loam
Caroline	12A	Ingleside sandy loam	Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Caroline	CrA	Corsica mucky loam	Fine-loamy, mixed, active, mesic Typic Umbraquults	Loam
Caroline	FaA	Fallsington sandy loam	Fine-loamy, mixed, active, mesic Typic Endoaquults	Sandy loam
Caroline	HbA	Hambrook sandy loam	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Caroline	IeB	Ingleside loamy sand	Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults	Loamy sand

County	Soil Abbreviation	Series	Description	Texture
Caroline	IgB	Ingleside sandy loam	Coarse-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Caroline	LhA	Lenni silt loam	Fine, mixed, active, mesic Typic Endoaquults	Silt loam
Carroll	MoB	Mount Airy and Manor soils	Loamy-skeletal, micaceous, mesic Typic Dystrudepts	Silt loam
Carroll	PeB2	Penn loam	Fine-loamy, mixed, superactive, mesic Ultic Hapludalfs	Loam
Carroll	PhB2	Penn silt loam	Fine-loamy, mixed, superactive, mesic Ultic Hapludalfs	Silt loam
Carroll	PnB2	Penn channery loam	Fine-loamy, mixed, superactive, mesic Ultic Hapludalfs	Loam
Cecil	CbC	Chillum silt loam	Fine-silty, mixed, semiactive, mesic Typic Hapludults	Silt loam
Cecil	MkB	Matapeake silt loam	Fine-silty, mixed, semiactive, mesic Typic Hapludults	Silt loam
Cecil	MxA	Montalto silt loam	Fine, mixed, semiactive, mesic Ultic Hapludalfs	Silt loam
Cecil	MzB	Mount Lucas silt loam	Fine-loamy, mixed, superactive, mesic Aquic Hapludalfs	Silt loam
Cecil	NtB	Neshaminy silt loam	Fine-loamy, mixed, superactive, mesic Ultic Hapludalfs	Silt loam
Charles	HgB	Hoghole-Grosstown complex	Sandy-skeletal, siliceous, mesic Typic Udorthents	Sand
Charles	LQA	Lenni and Quindocqua soils	Fine, mixed, active, mesic Typic Endoaquults	Silt loam
Dorchester	14A	Galestown loamy sand	Siliceous, mesic Psammentic Hapludults	Loamy sand
Dorchester	16	Hammonton sandy loam	Coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults	Sandy loam
Dorchester	18	Hurlock sandy loam	Coarse-loamy, siliceous, semiactive, mesic Typic Endoaquults	Sandy loam
Dorchester	21	Klej-Hammonton complex	Mesic, coated Aquic Quartzipsamments	

County	Soil Abbreviation	Series	Description	Texture
Dorchester	29	Pone mucky loam	Coarse-loamy, siliceous, active, mesic Typic Umbraquults	Loam
Frederick	MeC	Mount Airy channery loam	Loamy-skeletal, micaceous, mesic Typic Dystrudepts	Loam
Frederick	PrA	Penn-Reaville silt loam	Fine-loamy, mixed, active, mesic Aquic Hapludalfs	Silt loam
Garrett	At	Atkins silt loam	Fine-loamy, mixed, active, acid, mesic Fluvaquentic Endoaquepts	Silt loam
Garrett	BsC	Brinkerton and Andover very stony silt loam	Fine-silty, mixed, superactive, mesic Typic Fragiaqualfs	Silt loam
Garrett	CtB	Cookport channery loam	Fine-loamy, mixed, active, mesic Aquic Fragiudults	loam
Garrett	DbB	Dekalb channery loam	Loamy-skeletal, siliceous, active, mesic Typic Dystrudepts	Sandy loam
Garrett	ErB	Ernest silt loam	Fine-loamy, mixed, superactive, mesic Aquic Fragiudults	Silt loam
Garrett	Lc	Lickdale silt loam	Fine-loamy over sandy or sandy-skeletal, mixed, active, acid, mesic Humic Endoaquepts	Silt loam
Harford	CcB2	Chester silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	Silt loam
Harford	EhB2	Elioak silt loam	Fine, kaolinitic, mesic Typic Hapludults	Silt loam
Howard	GaB	Galen very fine sandy loam	Coarse-loamy, mixed, active, mesic Oxyaquic Hapludalfs	Sandy loam
Howard	GbC	Gladstone loam	Fine-loamy, mixed, active, mesic Typic Hapludults	Loam
Howard	GmB	Glenville silt loam	Fine-loamy, mixed, active, mesic Aquic Fragiudults	Silt loam
Kent	BuA	Butlertown-Mattapex silt loam	Fine-silty, mixed, semiactive, mesic Typic Fragiudults	Silt loam
Kent	MxA	Mattapex-Matapeake-Butlertown silt loam	Fine-silty, mixed, active, mesic Aquic Hapludults	Silt loam

County	Soil Abbreviation	Series	Description	Texture
Montgomery	17B	Occoquan loam	Fine-loamy, mixed, semiactive, mesic Inceptic Hapludults	Loam
Queen Anne's	GfB	Galestown-Fort Mott loamy sand	Siliceous, mesic Psammentic Hapludults	Loamy sand
Queen Anne's	MtA	Mattapex-Butlertown silt loam	Fine-silty, mixed, active, mesic Aquic Hapludults	Silt loam
Queen Anne's	PiB	Pineyneck silt loam	Coarse-loamy, mixed, active, mesic Aquic Hapludults	Silt loam
Queen Anne's	UsA	Unicorn-Sassafras loam	Coarse-loamy, mixed, semiactive, mesic Typic Hapludults	Loam
Saint Mary's	BlB2	Beltsville silt loam	Fine-loamy, mixed, semiactive, mesic Typic Fragiudults	Silt loam
Saint Mary's	KeC3	Kempsville fine sandy loam	Fine-loamy, siliceous, subactive, thermic Typic Hapludults	Sandy loam
Saint Mary's	MtB2	Mattapex fine sandy loam	Fine-silty, mixed, active, mesic Aquic Hapludults	Sandy loam
Saint Mary's	SmC2	Sassafras-Chillum complex	Fine-loamy, siliceous, semiactive, mesic Typic Hapludults	Sandy loam
Somerset	FgA	Fallsington silt loam	Fine-loamy, mixed, active, mesic Typic Endoaquults	Silt loam
Somerset	FhA	Fallsington-Glassboro complex	Fine-loamy, mixed, active, mesic Typic Endoaquults	Silt loam
Somerset	HmA	Hammonton loamy sand	Coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults	Loamy sand
Somerset	LO	Longmarsh and Indiantown soil	Coarse-loamy, siliceous, active, acid, mesic Fluvaquentic Humaquepts	Mucky loam
Somerset	MdA	Manokin silt loam	Fine-loamy, mixed, active, mesic Aquic Hapludults	Silt loam
Somerset	OKA	Othello and Kentuck soil	Fine-silty, mixed, active, mesic Typic Endoaquults	Silt loam

County	Soil Abbreviation	Series	Description	Texture
Somerset	OtA	Othello silt loam	Fine-silty, mixed, active, mesic Typic Endoaquults	Silt loam
Somerset	QeB	Queponco silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults	Silt loam
Somerset	QuA	Quindocqua silt loam	Fine-loamy, mixed, active, mesic Typic Endoaquults	Silt loam
Talbot	CsA	Crosiadore silt loam	Fine-silty, mixed, active, mesic Aquic Hapludults	Silt loam
Talbot	NsA	Nassawango silt loam	Fine-silty, mixed, semiactive, mesic Typic Hapludults	Silt loam
Washington	DsB	Duffield silt loam	Fine-loamy, mixed, active, mesic Ultic Hapludalfs	Silt loam
Washington	HaB	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs	Silt loam
Washington	RmB	Ryder-Duffield channery silt loam	Fine-loamy, mixed, semiactive, mesic Ultic Hapludalfs	Silt loam
Washington	SsA	Swanpond-Funkstown silt loam	Very-fine, mixed, active, mesic Vertic Paleudalfs	Silt loam
Wicomico	BhA	Berryland mucky loamy sand	Sandy, siliceous, mesic Typic Alaquods	Mucky loamy sand
Wicomico	FmA	Fort Mott loamy sand	Loamy, siliceous, semiactive, mesic Arenic Hapludults	Loamy sand
Wicomico	MuA	Mullica-Berryland complex	Coarse-loamy, siliceous, semiactive, acid, mesic Typic Humaquepts	Sandy loam
Wicomico	MvA	Monmouth fine sandy loam	Fine, mixed, active, mesic Typic Hapludults	Sandy loam
Wicomico	RkA	Rockawalkin loamy sand	Loamy, mixed, semiactive, mesic Aquic Arenic Hapludults	Loamy sand
Worcester	As	Askecksy loamy sand	Siliceous, mesic Typic Psammaquents	Loamy sand
Worcester	CeA	Cedartown-Rosedale complex	Siliceous, mesic Psammentic Hapludults	Loamy sand

County	Soil Abbreviation	Series	Description	Texture
Worcester	Em	Elkton silt loam	Fine-silty, mixed, active, mesic Typic Endoaquults	Silt loam
Worcester	KsA	Klej loamy sand	Mesic, coated Aquic Quartzipsamments	Loamy sand
Worcester	RuA	Runclint loamy sand	Mesic, coated Lamellic Quartzipsamments	Loamy sand

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