

**Relationship between Chemical Analyses of P in Soil
and P Loss in Simulated Runoff**

BY

Clayton Ashley David Sawka

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

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University of Manitoba
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ABSTRACT

Surface soil (0-15 cm) was collected from 39 fields from agricultural Manitoba with varying pH, texture and soil test P (STP) values and used in a series of laboratory simulated rainfall experiments. Soils were packed into soil boxes and placed on a table with a 5% slope, where they were subjected to 75 mm hr⁻¹ of simulated rainfall until they generated 90 minutes of continuous runoff.

Soil test P methods that were evaluated included: Olsen (sodium bicarbonate), Mehlich 3, Modified Kelowna, and water. Degree of P saturation was calculated as a ratio of STP to phosphorus sorption capacity estimated using Mehlich 3 extractable Ca and Mg or single point isotherm methods.

Runoff water was collected at time intervals of 0-30, 30-60, and 60-90 minutes after the initiation of continuous runoff. Results indicated that STP and total dissolved P (TDP) in runoff water were strongly related, with Olsen P providing the strongest relationship with TDP regardless of textural classification during the initial 30 minutes of runoff ($r^2 = 0.77$) and for the entire duration of the rainfall event ($r^2 = 0.75$).

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ABBREVIATIONS

P	- Phosphorus
TDP	- Total Dissolved Phosphorus
SRP	- Soluble Reactive Phosphorus
PP	- Particulate Phosphorus
DP	- Dissolved Phosphorus
STP	- Soil Test Phosphorus
Ols-P	- Olsen P
WEP	- Water Extractable P
MK-P	- Modified Kelowna P
M3-P	- Mehlich 3 P
DPS	- Degree of Phosphorus Saturation
M3CaMg	- Mehlich 3 extractable Ca and Mg
P150	- P Isotherm from 150 ppm P
PSI	- Phosphorus Sorption Index
PSC	- Phosphorus Sorption Capacity
EDI	- Effective Depth of Interaction
RO	- Reverse Osmosis
OX	- Oxalate extractable
S _{max}	- Phosphorus Adsorption Maximum

1.0 Introduction

In the mid 1970s, researchers began to recognize eutrophication as being the result of with-in lake processes and land-water interactions (Schindler, 1977). Schindler (1977) showed that elevated concentrations of phosphorus (P) in particular had the largest impact on the algal communities. These cyanobacteria generally fix their own nitrogen and P is the main nutrient limiting growth (Schindler, 1977). During the 1970s there was a public effort to eliminate point sources of P and to stop the flow of P into waterways. Prior to this discovery, people thought it was best to attack the resulting algal growth with herbicides (Schindler, 2006). Afterwards, the removal of P from human waste and detergents were the main targets for policy changes and improvements were observed in many lakes.

Point sources of P loading such as the discharge of municipal wastewater are relatively easy to identify and manage. However, in watersheds where soils are rich in nutrients there is a substantial risk of non-point source nutrient loading which is difficult to combat. For example, within Manitoba, agriculture has been identified as supplying 15% of the P load in Lake Winnipeg (Lake Winnipeg Stewardship Board, 2006). Of that 15%, the majority of the P is in the dissolved and readily available form (Glozier et al., 2006; Sheppard et al., 2006). With agriculture now identified as a source of P loading the next challenge is to identify the characteristics of agricultural land and its management that are contributing to P loss and eventually eutrophication. Source factors include the P content of the soil and the nutrient management practices on that parcel of land such as the P application rate, timing and type of P (synthetic fertilizer or manure) that is applied (Heathwaite et al., 2005a; Kleinman et al., 2002). The transport mechanisms are usually

accounted for in the P indices that have been developed using an erosion estimator such as the Revised Universal Soil Loss Equation (Sharpley et al., 2001a) and are usually erosion or runoff water driven.

Beneficial management practices (BMPs) have been developed to reduce the impact that agricultural P may have on nearby surface or ground water. A phosphorus BMP is generally considered to be a practice that minimizes the risk of agricultural P moving into surface or ground water and causing problems with the health of that aquatic system. For example, subsurface placement of manure either through incorporation by tillage, direct injection of liquid manure, or banded synthetic fertilizer helps to reduce the amount of exposure the manure P has to precipitation (snow or rain). Subsurface placement of fertilizer or manure decreases the exposure of added P to runoff and increases exposure of P to the soil particles which adsorb the labile P. Such retention of P by soil particles reduces the risk of P loss, provided that the area is not subject to water erosion that could carry P loaded particulate and colloidal material to a nearby stream.

Timing of fertilizer and manure application is also important to reduce potential impacts. In the Canadian prairies, where soils are frozen and snow covered for the winter period, timing becomes very crucial. If fertilizer or manure is surface applied on to soils too late in the fall and the cold soils have not had a chance to bond with the added P then this P is left exposed to snow melt in the spring, when 80% of runoff occurs in this region (Nicholaichuk, 1967). However, spring application of manure and fertilizer is generally limited by time constraints, especially with relatively short growing seasons with little time to apply manure and seed. Therefore, fall application of fertilizer and manure is regarded by farmers as a necessity.

One of the transport BMPs that is often recommended to reduce P movement is to plant vegetative buffer strips along waterways. Buffer strips are most effective at slowing the movement of particulate P (PP). However, although the total P (TP) load may decrease, the proportion of TP that is dissolved may increase and the dissolved P (DP) is the portion that is the most bioavailable to cyanobacteria. This is also true for zero or no till fields that leave the vegetative residues on the surface of the soil. As a result the proportion of dissolved P increases in a zero till system far above that of conventionally tilled soil (Glozier et al., 2006; Heathwaite et al., 2005a; Sharpley and Smith, 1994). Researchers in Alberta have determined that DP forms the majority of P lost in runoff and that in most cases >90% of runoff was snowmelt driven (Little et al., 2007). Sheppard et al. (2006) also found that the majority of the P that is mobile during a snowmelt runoff event is dissolved P and that this P is not generally intercepted by vegetative buffer strips since the plants are not yet actively growing and may also be supplying P to the system.

Particulate phosphorus is a significant form of P loss in areas that are prone to water erosion; however, the bioavailability of that P is generally regarded as lower than for DP (McDowell and Wilcock, 2007). However, Uusitalo et al. (2003) showed that the bioavailability of P that is bound to soil particles can be important in water bodies. Conversely, Turner et al. (2004a) have demonstrated in systems with calcareous soils that the pH may never reach the point where P may be solubilized from soil colloids and may not be available. Most of the BMPs that have been developed have concentrated largely on reducing PP losses by reducing water erosion. Therefore, in areas where water erosion is substantial, reducing PP losses will significantly reduce TP losses. Soil

colloids, between 1 μm and 1 nm in diameter (Kretzschmar et al., 1999), may play a particularly important role in P retention and loss because of their large surface area and high capacity to adsorb P due to a large surface area (Heathwaite et al., 2005a; Kretzschmar et al., 1999; Turner et al., 2004a). However, these particles are also so small that they have the ability to stay suspended in the water column for extended periods of time which adds to their ease of transport and bioavailability to aquatic organisms (Kretzschmar et al., 1999). With such a wide range of size, some colloids may be passing through the 0.45 μm filter that is used to operationally define “dissolved” P. This could mean that true dissolved P is being overestimated (Hudson et al., 2000). However, there are many other factors that affect the bioavailability of PP such as soil to solution ratio and the ability of microorganisms to strip the sorbed P (Turner et al., 2004a); therefore, the desorbability of the P on these particles once they enter the stream is important (Uusitalo et al., 2001).

Environmentally and agronomically available P concentration in the soil as indicated by soil test P (STP) extractions has been identified as potentially the most reliable indication of P available for loss (Guidry et al., 2006; Kleinman et al., 2002; Kleinman et al., 2004; McDowell and Sharpley 2001; McDowell et al., 2000; Pote et al., 1999b; Torbert et al., 2002; Wright et al., 2006). Some of the common agronomic and environmental STP methods in North America and Europe include: Mehlich, Olsen, Bray, water, and Modified Kelowna. Soil has a limited capacity to retain P and when that capacity is saturated from excessive P application, the risk of P movement increases dramatically. The sources of excess P content in soil comes mainly from the over

application of synthetic P fertilizer or from a history of manure application (Turner et al., 2004a, b); however, application of municipal biosolids also elevates soil P.

There is some debate in the literature as to which method of measuring P in the soil can be best used to predict P losses. Some researchers recommend water extractable P (WEP) or 0.01M CaCl₂ to best represent the true interaction of rain water with soil to predict P losses under rainfall (Vadas et al., 2005). These are considered to be environmental soil P tests and are considered by some researchers to be more accurate than the agronomic methods for predicting P loss (Pote et al., 1996). The agronomic methods are generally stronger extractions such as Mehlich-3 or the Olsen P extraction that have been developed to mimic the plant soil interactions over an entire growing season that slowly mobilize the P that is bound to soil particles and not readily available to a weak extractant such as rain water.

Many studies have shown strong relationships between a variety of agronomic and environmental STP methods and soluble reactive P (SRP) in runoff water (Ebeling et al., 2003; Fang et al., 2002; Kleinman et al., 2004; McDowell et al., 2000; Pote et al., 1999b; Torbert 2002; Wright et al., 2006; Wright et al., 2003). However, there is no consensus in the literature as to which STP method is best for estimating SRP or TDP in runoff water. Vadas et al. (2005) tried to develop a single extraction coefficient from the data that others produced. They compared studies that used packed soil boxes and field plots separately. When the six packed soil box studies were evaluated, there were no significant differences among the coefficients for the ten soils used when P was extracted using Bray-1 or Mehlich-3 P. The same was true for the field studies, except for one soil used by Cox and Hendricks (2000) which had extremely low clay content (5%) and had

only five observation points. Clay content of the soil affected the ability of the soil to buffer P loss. In the Cox and Hendricks (2000) study the soil that contained 32% clay required almost three times more STP as the soil that contained 5% clay to yield a concentration of 1 mg L^{-1} in runoff. Vadas et al. (2005) went on to compare environmental STP methods and found that 17 of the 20 soils showed no significant difference in the extraction coefficients. The three soils that were different showed no obvious chemical or physical properties that would have caused them to behave differently.

Pote et al. (1996) found relationships between SRP in runoff water and ammonium oxalate, iron oxide strips and water extractable P (WEP), all of which are considered to be environmental STP methods. This was also the case with Pote et al. (1999) and Schroeder et al. (2004) when the data was normalized with the volume of runoff expressed as a depth of water over the runoff area. The data was normalized in this fashion because of the drastically different quantities of runoff that were collected from each of the soils used in the experiment. Converting the runoff concentrations to this P load oriented approach allowed better comparisons between soils that varied in texture. As a result, Pote et al. (1999) found excellent relationships with SRP in runoff and STP in soil regardless of what soil test method was used. Conversely, other researchers found that normalizing the data did not significantly change the correlations between soil test methods (Davis et al., 2005; Kleinman et al., 2004; Torbert, 2002). In fact, Kleinman et al. (2004) found that the variability among soil tests was increased when P concentrations were converted to P load.

There is also evidence to suggest that STP methods reveal a “change point” where the concentration of P in runoff or leachate water increases sharply with a small increase in STP (Heckrath et al., 1995; McDowell and Sharpley, 2001; McDowell et al., 2000). McDowell et al. (2000) demonstrated this phenomenon in a variety of soils from New Zealand, the United Kingdom and the United States; however, the change point was not observed in every soil. The split line model used in the McDowell study was most frequently observed with the Olsen P method; however, their study was not conducted using true runoff, but rather by plotting STP against CaCl₂ extractable P to simulate the relationship between STP and P in soil solution (McDowell et al., 2000). A similar split line relationship was observed by Heckrath et al. (1995) in the relationship between percolate P and Olsen P in the plow layer. Conversely, a study done in Alberta with simulated rainfall runoff showed linear regressions without any change points for all six of the STP methods evaluated including WEP and Mehlich-3 which have been shown to exhibit a change point in other studies (Wright et al., 2006).

Due to this lack of coherence among traditional environmental and agronomic soil tests for P some researchers have suggested that the degree of phosphorus saturation (DPS) may be a better representation of how well the soil will retain or release P. Degree of P saturation has been defined by Casson et al. (2006) as:

$$[1] \quad \text{DPS (\%)} = \frac{\text{Measurement of P sorbed (mg kg}^{-1}\text{)}}{\text{P sorption capacity (mg kg}^{-1}\text{)}} \times 100$$

As soils become more saturated with P there is greater potential for the soil solution to maintain a high concentration of available P especially if P rich soil is washed into waterways and then available for desorption (Paulter and Sims, 2000). For example,

Pautler and Sims (2000) showed that in the excessive STP range soils had 13% P available to Fe-oxide strips where in the low STP soil there was only 1% P available and DPS may account for this change in labile P behaviour.

Some of the methods of determining DPS described in the literature use oxalate extractable P or Mehlich-3 P as the numerator and oxalate or Mehlich-3 Al plus Fe as the denominator, as an estimate of P sorption capacity (PSC) (Sharpley, 1995; Sims et al., 2002). Extractable Fe and Al are used for estimating DPS in acid soils because these are the ions that are most responsible for P adsorption. These denominator values are sometimes multiplied by an alpha value (Maguire and Sims 2002b; Sims et al., 2002). The alpha value is a saturation factor to account for the percentage of the Fe and Al in the soil that contributes to the adsorption of P to the soil particles (Ige et al., 2005a). The alpha value is generally between 0.4 and 0.6 for noncalcareous soils (Sims et al., 2002).

As an alternative to using Mehlich 3 or oxalate extractable Al and Fe some researchers have used Langmuir adsorption isotherm values (Casson et al., 2006; Fang et al., 2002; Sharpley, 1995). Others have used the P sorption index (PSI) to estimate the PSC (Pote et al., 1999b). Using these methods of determining DPS has been shown to be a better estimator of potential for P loss than Mehlich-3 P alone because other soil properties for P retention are taken into account (Sims et al., 2002). As with STP methods, DPS measurements have revealed change point behaviour, where the concentration of P in runoff water increases rapidly at a threshold P saturation (P_{sat}) (Maguire and Sims, 2002b; McDowell and Sharpley, 2001; McDowell et al., 2000; Nair et al., 2004). However, threshold values using DPS were not always present in these studies and sometimes varied greatly with soil.

Manitoba's agricultural soils are rarely acidic and generally have very low quantities of Fe and Al; therefore, these ions are not the primary factors responsible for P retention. In calcareous soils, Ca and Mg are present in high concentrations and are the main ions responsible for P retention (Ige et al., 2005b). Therefore, some researchers have hypothesized that the extractable Ca + Mg might be used for estimating DPS in calcareous soils, in the same fashion as extractable Fe + Al is used in acidic soils (Ige et al., 2005a; Kleinman and Sharpley 2002). Ige et al. (2005b) and Kleinman and Sharpley (2002) have demonstrated that oxalate extractable Al + Fe provides a poor estimate of PSC in alkaline soils. In contrast, using Mehlich-3 (M3) extractable Ca + Mg to estimate PSC in DPS calculations provided a relatively reliable estimate of potential for P release to water (Ige et al., 2005a, b; Kleinman and Sharpley 2002). Kleinman and Sharpley (2002) showed that using a ratio of M3-P to M3 Ca had a strong linear relationship with P_{sat} estimated using a Langmuir sorption maximum ($r^2 = 0.84$), suggesting that M3-P may be suitable for predicting P loss from alkaline soils.

An additional challenge in calculating DPS is accounting for P existing in soil when estimating PSC. This challenge is especially significant in soils with high concentrations of P. For example, Akinremi et al. (2007) showed that the DPS methods originally developed by Ige et al. (2005b) were not accurate in soils that received frequent applications of livestock manure. Therefore, Akinremi's group modified their DPS equations to account for the "native" P present in the soil by adding the measured P into the estimate of PSC. Accounting for native P when estimating PSC resulted in DPS values that did not exceed 100%; a problem that occurred when using original DPS equations on soils with a history of manure additions. Pautler and Sims (2000) and

Kleinman and Sharpley (2002) also incorporated STP into their estimate of PSC and P_{sat} , respectively.

Most studies where P concentrations in soil and runoff are well correlated have been conducted with a rainfall simulator under field or laboratory conditions (Cox and Hendricks, 2000; Davis et al, 2005; Kleinman et al., 2004; Schroeder et al., 2004; Sharpley and Moyer, 2000; Wright et al., 2006). Packed soil boxes in laboratory conditions have been used to minimize any variability there may be between simulation replicates in the soil or in the rainfall simulations themselves (Kleinman et al., 2004). Wright et al. (2003) found that P concentration in runoff loss increased when the runoff was measured under field conditions as opposed to packed soil boxes. One reason for the relatively low concentration of P in runoff from laboratory studies is the high rate of rainfall required to generate runoff in disturbed soils. The increased runoff is also a relic of the soil boxes being sieved and packed without any of the natural preferential flow channels that may exist in field conditions (Kleinman et al., 2004). Along with the increased flow the composition of the runoff may be affected slightly with the use of packed soil boxes. Little et al. (2007) thought that the use of packed soil boxes may cause total phosphorus to have an elevated proportion made up from particulate P (PP). In some cases the composition of TP from packed soil boxes could be made up of 98-99% PP (Fang et al., 2002; Kleinman et al., 2004). However, despite there being differences between packed soil boxes and in field rainfall simulations Kleinman et al. (2004) showed that either can be used with good success for predicting P loss in runoff.

In summary, many studies have been conducted on acidic soils high in Fe and Al to show how various STP or DPS methods can be used to predict runoff P losses.

However, little research has been conducted on predicting runoff P losses from soils that are neutral to alkaline with relatively high clay content. Therefore, the objective for our study was to determine the relationship between a variety of STP and DPS methods and P in runoff and leachate for typical neutral to alkaline soils in agricultural Manitoba.

With this objective in mind, simulated rainfall experiments were conducted on packed soil boxes using a selection of soils with a range of physical and chemical properties commonly found in southern agricultural Manitoba soils.

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Dissolved Phosphorus Concentrations and Loads Lost from Manitoba Soils under Simulated Rainfall

2.0 Abstract

Simulated rainfall studies with packed soil boxes were conducted to determine relationships between total dissolved P (TDP) in runoff water and several measures of soil test phosphorus (STP) and degree of P saturation (DPS). Surface soil (0-15 cm) was collected from 39 fields from agricultural Manitoba with varying pH, texture and STP values and used in a series of laboratory simulated rainfall experiments. STP methods that were evaluated included: Olsen (sodium bicarbonate), Mehlich 3, Modified Kelowna, and water. Degree of P saturation, measured as a ratio of STP to an estimate of phosphorus sorption capacity using Mehlich 3 extractable Ca and Mg or single point isotherms, was also calculated and related with TDP. Runoff water was collected at time intervals of 0-30, 30-60, and 60-90 minutes after the initiation of continuous runoff. Results indicated that STP and TDP in runoff water were strongly related, with Olsen P providing the strongest relationship with TDP regardless of textural classification during the initial 30 minutes of runoff ($r^2 = 0.77$) and for the duration of the rainfall event ($r^2 = 0.75$).

2.1 Introduction

Agronomically insignificant amounts of phosphorus (P) have been shown to cause substantial negative effects on aquatic life in freshwater due to eutrophic conditions (Schindler, 1977). As a result, the non-point sources and pathways for P losses from agricultural fields have been the focus of extensive research over the last two decades (Pautler and Sims, 2000). Many of the studies have concentrated on estimating the amount of P in the system that is susceptible to loss and the mechanisms by which that P is transported into water bodies. Site specific indices have been developed to help identify high risk areas using a combination of these source and transport factors (Lemunyon and Gilbert, 1993). Source factors that have been identified are rate of P applied, placement, timing of the P and the amount of existing P in the soil (Kleinman and Sharpley 2002). All of these influence the availability of P to transport factors and ultimately loss.

The two forms P that can be transferred from the field into surface water are dissolved P (DP) and particulate P (PP). Particulate P is attached to soil particles and will move only if the soil particle is mobilized; i.e. lost due to erosion processes. Dissolved P may be a combination of truly soluble P that is operationally defined as P that will pass through a 0.45 μm filter and fine colloidal P that is not truly dissolved but may pass through a 0.45 μm filter. Dissolved P remains soluble or suspended in soil solution and can be carried away in very slow moving water (Haygarth and Sharpley, 2000; Haygarth et al., 1997). Dissolved P can be further separated into molybdate reactive P (Murphy and Riley, 1962) which is also known as soluble reactive P (SRP) and non-reactive P, most of which is generally assumed to be organic P (Haygarth and Sharpley, 2000).

Soluble reactive P is assumed to be the most biologically available (Haygarth et al., 1997).

Soils that have been identified as having the greatest risk to loss are usually soils that have high agronomic soil test phosphorus (STP) values (Pautler and Sims, 2000). As a result, high STP values often correspond with high P concentrations in runoff water (Davis et al., 2005; Fang et al., 2002; McDowell and Sharpley, 2001; McDowell et al., 2000; Pote et al., 1996; Schroeder et al., 2004). However, there is no consensus in the literature as to which STP method provides the most accurate prediction of P loss. Several agronomic STP methods have shown strong relationships with P in runoff water. Among the STP methods evaluated are Mehlich-1, Mehlich-3, Olsen, Bray-1, Kelowna, and Modified Kelowna (Fang et al., 2002, McDowell et al., 2000; Pote et al., 1999b; Pote et al., 1996; Torbert et al., 2002; Vadas et al., 2005; Wright et al., 2006). Some researchers have theorized that STP methods that have been developed for agronomic measurements of available P are not an accurate indicator of P that will be susceptible to loss in runoff. Agronomic soil tests are generally more aggressive than rain or snowmelt water would be and are made to simulate the nutrient mining ability exhibited by plant roots. Based on this, less aggressive, environmental methods have been developed which include deionized water or water extractable P (WEP) (Pote et al., 1996; Pote et al., 1999b) as well as using dilute salt concentrations such as 0.01M CaCl₂ (McDowell et al., 2000) to simulate the ionic strength of soil solution.

Depending on the type of soil being used, all of the extraction methods mentioned previously have shown strong relationships with either total dissolved P (TDP) or soluble reactive P (SRP). For example, in a study done in Alberta with packed soil boxes,

researchers found r^2 values of 0.74, 0.93, and 0.96 for the linear regression relationship between TDP in runoff and WEP, Mehlich 3-P and Modified Kelowna tests, respectively (Wright et al., 2006). In the U.S., Pote et al. (1996) also found that STP concentrations accounted for >70% of the variation in runoff P concentrations. The Bray-1 analysis is a good predictor of runoff P in acid soils (Pote et al., 1996) but not in soils that are calcareous (Fang et al., 2002). Mehlich-3, however, has been used successfully in calcareous soils. The Olsen-P method is also a reliable predictor in these conditions (Fang et al., 2002; Guidry et al., 2006; Kleinman and Sharpley, 2002). Mehlich-3 may be a good predictor in calcareous soils but may overestimate P losses from soils that have a history of manure application (Kleinman and Sharpley, 2002).

Simulated rainfall experiments under laboratory conditions help to minimize extenuating variables that may affect runoff in field experiments. Soils are inherently variable and even when two soils have been packed to similar bulk densities, differences in runoff will occur. Because of differences in hydrology from packed soil boxes, some researchers have found it beneficial to normalize the data and use P loads expressed as a depth of runoff rather than concentration in runoff (Pote et al., 1999b; Schroeder et al., 2004). Normalizing by catchment area can also provide a strong relationship with STP methods (Kleinman et al., 2004). After this conversion of runoff P concentration to a mass of P lost expressed as a depth of runoff, both Pote et al. (1999b) and Schroeder et al. (2004) showed strong linear relationships with WEP and runoff P. However, Kleinman et al. (2004) found that using runoff depth was a poor indicator of P loss and normalizing by catchment area provided the strongest regressions with SRP and STP.

It has been argued that STP does not take into consideration the phosphorus sorption capacity (PSC) of the soil; as a result, the concept of degree of P saturation (DPS) was developed. To account for the ability of individual soils to retain P as well as the soil's concentration of available P, a typical general equation for DPS is defined by Casson et al. (2006) as:

$$[1] \quad \text{DPS (\%)} = \frac{\text{Soil P concentration (mg kg}^{-1}\text{)}}{\text{P Sorption Capacity (mg kg}^{-1}\text{)}} \times 100$$

Generally, DPS values less than 25-40 % for most soils have been accepted and shown to be a low risk for P losses (Pautler and Sims, 2000). For sandy soils, this threshold may be lower, due to the limited PSC and has been reported as low as 16-20% for Florida soils (Nair et al., 2004). Some methods for determining PSC employ a P sorption index or Langmuir models to estimated sorption maximum (S_{\max}) (Pautler and Sims 2000). However, most common methods for determining PSC in North America use Mehlich-3 (M3) or oxalate (Ox) extractable Fe and Al (Kleinman and Sharpley, 2002; Maguire and Sims, 2002b; Nair et al., 2004; Pautler and Sims 2000; Pote et al., 1996) because these are the ions that are most effective in retaining P in acidic soils. However, in neutral to alkaline soils where Ca and Mg dominate P sorption processes, the amount of Fe and Al does not have the same influence (Ige et al., 2005a, b; Kleinman and Sharpley, 2002). Kleinman and Sharpley (2002) concluded that M3 extractable Ca would be a useful estimator of PSC in calcareous soils. They found that a ratio of M3-P / M3 Ca accounted for 84% of the variation their standard DPS values measured as bicarb P / (S_{\max} (Langmuir) + bicarb P) in these soils. Ige et al. (2005a, b) used similar equations and also found strong correlations between WEP values and either Olsen P / M3(Ca+Mg) or

Mehlich 3 P / $M3(Ca+Mg)$. Subsequently, Akinremi et al. (2007) amended these equations by adding STP back into the denominator. This modification was necessary for soils that had a history of manure application and, therefore, a large proportion of their P sorption capacity was already saturated, leading to these soils apparently having over 100% saturation when DPS was calculated using the original equations developed by Ige et al. (2005a, b).

Environmental thresholds for soil P are often determined by the “change point” where the concentration of P in runoff increases rapidly with every unit of increase of P saturation or STP. This change point threshold has been shown in soils from all over the world (Casson et al., 2006; McDowell and Sharpley 2001; McDowell et al., 2000; Nair et al., 2004) but not always in every soil. For example, Torbert et al. (2002) and Wright et al. (2006) did not observe any such change points in their soils.

Packed soil boxes in rainfall simulation studies are commonly used to determine the relationships between soil and runoff P (Davis et al., 2005; Fang et al., 2002; Guidry et al., 2006; Kleinman and Sharpley 2002; Kleinman et al., 2004; McDowell and Sharpley, 2001; Sharpley, 1995; Wright et al., 2006). Most of the studies are standardized with respect to soil box size (National Phosphorus Research Project, 2005) and the rainfall simulator used (Humphry et al., 2002). The use of packed soil boxes allows for uniformity in aggregate size, bulk density, slope and moisture content (Kleinman et al., 2004) whereas these are not controlled with in situ simulated rainfall on field plots. Rainfall simulators in turn allow for a constant delivery of water at a repeatable rate and duration of rainfall. However, the rainfall simulation over packed soil boxes tends to yield more PP losses than for field plots (Little et al., 2007). Some

researchers have observed greater runoff from packed boxes than from field plots (Guidry et al., 2006; Kleinman et al., 2004) and this was attributed the bare soil that was prone to erosion.

One of the methods used to compare rainfall simulation studies across soils is to compare the slope of the linear regression line from STP methods and runoff SRP, commonly referred to as the extraction coefficient (Vadas et al., 2005). Kleinman et al., (2004) found little differences in extraction coefficients from field plots to soil boxes. In 26 of 31, soils extraction coefficients did not vary significantly when comparing packed boxes to field plots with M3 or Bray-1 P soil tests (Vadas et al., 2005). Results differ when moving from packed boxes to whole watersheds, where packed boxes have been shown to greatly underestimate the concentration of P in runoff (Little et al., 2007; Wright et al., 2003). In a study done in Alberta the average concentration of P in watershed runoff was 5.9 times higher than predicted from laboratory rainfall simulation studies (Wright et al., 2003).

Our study used packed soil boxes in a rainfall simulator to determine the relationship between runoff P and soil P for a variety of soils from across agricultural Manitoba. The specific objectives of this experiment were to determine: (1) what common agronomic or environmental STP method (Olsen, Mehlich-3, WEP, or Modified Kelowna) would be the most dependable predictor of runoff P from typical Manitoba soils; (2) if newly developed DPS methods for calcareous soils (Akinremi et al., 2007; Casson et al., 2006; Ige et al., 2005a, b) would improve our ability to predict P runoff across a variety of soils.

2.2.0 Materials and Methods

2.2.1 Soil Collection

Soils from agricultural Manitoba were collected from 39 sites in the fall of 2005 and 2006. Samples were collected at the end of the growing season and after harvest for all sites except for 7 fields. Four of these fields were seeded to corn and still had not been harvested and three of the fields were grazed pasture land. Twenty three of the fields sampled had a long history of manure application. The histories of the remaining fields are not as well known but in recent history received only synthetic sources of P. Generally, the manure had been applied approximately one year prior to collection and had a full growing season for the soil to equilibrate with the manure. In two of the fields, the farmers had already begun their application of manure the day before soil collection. In these two fields the solid manure had been surface applied and not yet incorporated; therefore, the fresh manure was scraped from the surface prior to sampling.

Soil was collected from a 9 by 9 m plot that was further divided into 9 – 3 by 3 m plots. Soil was cleared of crop residue or sod was shaved off and then samples from the 0-15 cm mineral soil layer of each 3 by 3 m area were collected one shovel full at a time into 8 separate 20-L pails. This way we could ensure that each pail contained a similar mixture of soil. A composite sample was taken by coring all of the pails with an auger; this sample was used for all physical and chemical analyses. The pails had small holes drilled into the side wall near the upper rim to allow for gas exchange. Lids were placed on the pails and stored in an unheated shed over winter until rainfall experiments were started in the early summer of 2006.

2.2.2 Soil Preparation and Analysis

Soils were analyzed for available P using the following extractants: Olsen (Ols-P) (Olsen et al., 1954), Mehlich-3 (M3-P) (Mehlich et al., 1984), Modified Kelowna (MK-P) (Qian et al., 1994), and water (WEP) (1:10 soil: solution, 1 hour extraction). Single point phosphorus adsorption isotherms were determined using a solution with P concentrations of 75 ppm (P75) (Casson et al., 2006) and 150 ppm (P150) (Ige et al., 2005a). Mehlich-3 and Modified Kelowna exchangeable Ca, Mg, Fe, and Al were also measured by ICP-AES. Soils were analyzed for texture (pipette method), pH and electrical conductivity (1:2, soil: solution) and carbonates.

Prior to runoff experiments, each soil was sieved at field moisture using a 10 mm steel mesh. In some cases (wet heavy clays) the moisture was 30-50% by weight and had to be air dried for 4-6 hours before sieving.

Soils were divided into two groups based on texture as defined by the Canadian textural triangle with <25% clay being a coarse and >26% clay as a fine textured soil; this division was chosen because soils that have at least 26% clay are defined as moderately fine to fine (Brady and Weil, 2008). Soils were packed into the soil trays at a bulk density ranging from 1 g cm^{-3} for fine textured soils to 1.2 g cm^{-3} for coarse textured soils. Soil trays were prewetted by establishing a water table at 9 cm below the soil surface to allow for capillary rise to wet soils (Wright et al., 2006). Pre-wetting was done to ensure runoff occurred from coarse soils and to reduce variability between soils. The pre-wet procedure took place over a 20 hour period, after which the soils were allowed to drain for a minimum of 60 minutes by gravity.

2.2.3 Degree of Phosphorus Saturation

Five general DPS formulas were used in this study, including four DPS formulas that have been generated for Manitoba soils (equations 2-5) and one for Alberta (equation 6) as follows:

$$[2] \text{ DPS}_{(P150)} \quad (\%) = \frac{STP}{P150} \times 100 \quad (\text{Ige et al., 2005a})$$

$$[3] \text{ DPS}_{(M3CaMg)} \quad (\%) = \frac{STP}{\alpha (Ca_{M3} + Mg_{M3})} \times 100 \quad (\text{Ige et al., 2005b})$$

$$\alpha = 0.2$$

$$[4] \text{ DPS}_{(P150+STP)} \quad (\%) = \frac{STP}{(2 \times P150) + STP} \times 100 \quad (\text{Akinremi et al., 2007})$$

$$[5] \text{ DPS}_{(M3CaMg+STP)} \quad (\%) = \frac{STP}{\alpha (Ca_{M3} + Mg_{M3}) + STP} \times 100 \quad (\text{Akinremi et al., 2007})$$

$$\alpha = 0.1$$

$$[6] \text{ DPS}_{(PSI+STP)} \quad (\%) = \frac{STP}{(PSI + STP)} \times 100 \quad (\text{Casson et al., 2006})$$

The STP methods used in DPS equations 2-5 were Ols-P and M3-P; for equation 6, all STP methods we used. Measures of PSC included P sorption maximum estimated from a single point P150 adsorption isotherm (Ige et al., 2005a). Mehlich 3 extractable Ca and Mg ($Ca_{M3} + Mg_{M3}$) was also used because Ca and Mg are largely responsible for P retention in calcareous soils (Akinremi et al., 2007; Ige et al., 2005a). Following the research by Casson et al. (2006) in Alberta, PSC was estimated using the phosphorus sorption index (PSI) determined using a $CaCl_2$ solution containing 75 mg P L⁻¹ as H_2PO_4 (Bache and Williams, 1971) and is calculated as:

$$[7] \quad \text{PSI (mg kg}^{-1}\text{)} = \frac{XV}{S}$$

where X = initial – final solution P (mg L⁻¹), V is the volume of the solution (L), and S is the soil weight (kg) (Casson et al., 2006).

2.2.4 Rainfall Simulator

The rainfall simulator that was used for these experiments was the same system used by Wright et al. (2006). The simulator had a single Fulljet ½-50WSQ nozzle (Spraying Systems, Wheaton, IL) centered 3 m above two soil trays. The trays were custom built out of stainless steel and measured 0.95 m by 0.5 m by 0.1 m (Wright et al., 2006). The bottom portion of the trays was separated from the top compartment by a coarse steel mesh, covered by an acrylic sheet which had 10% of the material removed with 25 mm holes cut at equally spaced intervals to allow for percolate to drain and be collected during runoff (Wright et al., 2003). This also allowed pre-wetting of the soil by capillary rise. An inert landscape fabric was used on top of the acrylic sheet to allow water to percolate through but to retain the soil within the top compartment. The soil trays were placed on a table with a 5% slope.

The simulator was calibrated to deliver a rainfall event equivalent to 75 mm hr⁻¹ at a nozzle pressure of 28 kPa. The rainfall varied by 20% across each soil tray, with the outer edges receiving slightly more rain than the inside area. However, there was a mean rainfall intensity of 75 mm hr⁻¹ for each tray. A rainfall event of this magnitude and duration is not typical for a Manitoba summer (1 in 50 year storm) but was selected in accordance to the National Phosphorus Research Project (2005) and to ensure that runoff was generated. Water used for the pre-wet process and the simulations was purified by

reverse osmosis (RO) since the City of Winnipeg's potable water supply has P added to combat lead contamination in the delivery system.

2.2.5 Rainfall Simulations and Runoff Collection

The simulations were conducted on each soil in duplicate and the concentration of nutrients in runoff water as well as runoff volumes and loads are expressed as averages (raw data for each duplicate are presented in Appendix XVI). Runoff was collected for a total of 90 minutes after continuous runoff was observed. For most soils continuous runoff was observed within 3-5 minutes after rainfall began. Runoff water was collected for three time intervals during the simulation; these were 0-30, 30-60 and 60-90 minutes. Runoff water was collected under vacuum into glass carboys (23 L) that had been acid washed and double rinsed with RO water. Each carboy was weighed to determine the volume of runoff and then agitated and a 1 L subsample was drawn off for analysis. Percolate water was also collected for the entire 0-90 minute period and the same suite of analyses were conducted on these samples.

2.2.6 Water Analyses

Runoff and percolate water were analyzed at the Fisheries and Oceans Canada Freshwater Institute in Winnipeg, MB. The nutrients analyzed for in runoff water were: soluble reactive P (SRP), total dissolved P (TDP), particulate P (PP), with total P (TP) determined as the sum of TDP and PP. The percolate sample analyses included all of the forms of nutrients previously mentioned except for PP.

Water samples were filtered (0.45 μm) within 24 hours of collection. Filtrate was used for all dissolved analysis and suspended material was then analyzed for PP. Soluble reactive P was determined on the filtered samples using molybdenum-blue under acidic conditions and P concentration was determined with a colourimeter (Murphy and Riley, 1962).

Particulate P was determined by ignition of the glass filter that was used to separate suspended material from the dissolved fraction. Once complete, the phosphorus is dissolved in a dilute HCl to convert P to orthophosphate and then P is determined as SRP.

The concentration of TDP was determined by photo-oxidizing the filtered extracts under acidic conditions with sufficient oxygen concentrations to fully oxidize organic P to inorganic forms. Upon completion of UV radiation, the TDP was determined colourmetrically using a Technicon Autoanalyzer^R and molybdenum-blue (Murphy and Riley, 1962).

2.2.7 Statistical Analysis

Simple linear regression analysis was performed as well as a test for homogeneity between the soil groups within a STP method using the PROC GLM function within SAS version 9.1 (SAS Institute, Cary, NC).

2.3.0 Results and Discussion

2.3.1 Soil Characteristics

The soils collected were divided into two textural groups based on percent clay content: a coarse textured group (< 25% clay) and a fine textured group (>26% clay) (Brady and Weil, 2008). The mean clay content for the coarse group was 10% and for the fine group 49%, (Tables 2.1 and 2.2) and ranged from 2% to 22% and 26% to 83% in each group respectively. The soil boxes were packed to bulk densities of ranging from 1 to 1.2 g cm⁻³ for fine to coarse textured soils, respectively. These differences in bulk density also affected the runoff volumes that were obtained from each textural group. The fine group had a mean runoff of 85% of the total water collected, with the remaining 15% collected as percolate; the coarse group had a mean runoff of 77% of the total water collected, with 23% as percolate.

2.3.2 Total Dissolved Phosphorus in Runoff

Runoff P from agricultural land can be divided into TDP and PP. The dissolved fraction is generally believed to be composed of the inorganic soluble reactive P (SRP) and dissolved organic P and is the fraction of greatest environmental concern. Dissolved P is also the dominant fraction in runoff from Canadian prairie watersheds (Sheppard et al., 2006; Glozier et al., 2006; Little et al., 2007). In this runoff study, SRP accounted for 87% of TDP averaged over all soils and collection periods. However, runoff for two soils from pastured sites had only 39% (F1) and 45% (C1) of TDP in the SRP form. Although both of these fields have a history of manure application, these two soils also

had the lowest concentrations of OIs-P (Table 2.1 and 2.2) suggesting that organic P may be the dominant source of P for runoff losses from pastures that are low in STP.

2.3.2.1 First 30 Minutes of Runoff

During the first 30 minutes of runoff, water extractable P (WEP) was strongly related with runoff P concentrations from coarse textured soils ($r^2=0.93$) (Table 2.3).

Some researchers have postulated that the WEP should provide the strongest relationships with runoff P concentrations because it best simulates rain water as an extractant (Pote et al., 1996; Vadas et al., 2005). For example, Pote et al. (1996) also found that WEP was strongly correlated ($r^2=0.82$) with runoff P losses. The soil that was used in their study was a silt loam (8% clay) with a wide range of extractable P.

However, in the fine textured soils used in our study, WEP accounted for only 52% of the variation in runoff TDP concentration (Table 2.3). Using a linear model, WEP seemed to over-predict losses at low STP values and under-predict losses at high STP values (Fig. 2.1a). The fine textured soils ranged in clay content from 26-83%, and the fine textured soils showed a curvilinear relationship between WEP and TDP. The relatively poor relationship between WEP and TDP for the fine textured group may be due to differences in the degree of interaction between water and soil in the two systems. The methodology of the WEP method uses a soil: solution ratio of 1:10 and a 1 hour extraction time. One hour of extraction allows the solution to thoroughly extract water soluble P from all soil particles. In this type of runoff experiment the soil that is interacting with the runoff water is restricted to the surface for fine textured soils, resulting in very brief and spatially limited interaction between soil and runoff water. For example, Sharpley (1985)

showed that depending on texture, rainfall rate and the slope, different soils vary in their effective depth of interaction (EDI) with runoff water. In Sharpley's study the Houston Black (50% clay) and the Ruston fine sandy loam (10% clay) with a rainfall rate of 70 mm hr⁻¹ had EDIs of approximately 5 mm and 9 mm, respectively (Sharpley, 1985). These EDI values emphasize that although the clay soils may produce greater volumes of runoff, the amount of soil that the runoff water comes in contact with may be much smaller.

The problem of varying runoff volumes and EDI between different soils was encountered by Schroeder et al. (2004) and Pote et al. (1999). In the studies done by Schroeder et al. (2004) and Pote et al. (1999), the data was normalized for differences in soil hydrological behavior by using a ratio of the SRP concentration to the depth of runoff water collected. This manipulation of the data improved the consistency of relationships between STP and SRP in the runoff across different soil types, especially for WEP. However, when this calculation was performed on our coarse textured soils the relationships between WEP and TDP in runoff deteriorated substantially from an $r^2=0.92^{***}$ before normalization to an $r^2=0.20$ after. However, with the fine textured soils the r^2 for WEP and SRP improved slightly with an $r^2=0.52^{***}$ before normalization and $r^2=0.58$ after, but this trend did not continue for the other STP methods. Kleinman et al. (2004) and Davis et al. (2005) also used this method to normalize their data and there was no improvement to their relationships of SRP and M3-P or WEP with relatively coarse soils.

Table 2.1. Selected chemical and physical properties for the coarse textured group of soils.

Soil Id	Texture	Clay	Sand	Carbonate	Olsen	Water	Modified	Mehlich 3	pH	Electrical	Mehlich 3	Mehlich 3	P150
					P	P	Kelowna P	P		Conductivity	Calcium	Magnesium	
				%	mg kg ⁻¹				ms cm ⁻¹		mmol kg ⁻¹		
C1	S	6	88	0.80	0.95	0.90	1.63	3.75	6.71	0.16	55.90	11.86	7.26
C2	SL	13	77	1.80	2.40	1.63	8.04	21.56	7.93	3.57	126.65	67.73	9.68
C3	SL	13	77	0.30	3.95	3.15	8.38	11.69	6.98	0.09	53.24	10.69	5.97
C4	SL	14	76	3.50	4.20	0.63	4.83	13.25	8.03	0.50	155.38	28.91	13.06
C5	LS	8	85	0	7.80	7.30	14.17	22.44	6.71	0.07	29.01	7.96	3.15
C6	LS	5	84	0.70	12.60	9.78	17.50	30.31	6.59	0.13	34.36	9.75	2.42
C7	SL	15	74	13.90	15.35	2.95	12.91	43.63	8.11	0.28	163.76	19.26	12.82
C8	L	22	49	4.10	16.70	9.43	14.67	50.38	8.17	0.34	146.49	72.64	11.77
C9	L	20	47	0.60	19.95	5.77	19.00	36.30	6.87	0.38	not measured		302.08
C10	SL	20	71	13.10	22.80	7.88	27.04	63.50	8.21	0.25	126.99	57.87	12.18
C11	L	20	44	0	33.10	10.18	36.60	54.40	6.03	0.42	not measured		262.50
C12	LS	11	82	1.00	33.30	12.05	46.67	68.94	6.83	0.26	64.50	11.83	6.85
C13	LS	8	86	0	35.15	16.48	47.38	83.19	6.47	0.10	37.24	8.23	4.27
C14	S	7	91	0.30	48.48	12.00	73.63	104.38	7.60	0.52	0.86	9.17	108.33
C15	S	7	90	2.99	63.23	11.96	72.63	128.88	7.54	0.33	1.70	12.76	118.75
C16	S	4	93	0.58	82.22	28.42	114.75	174.00	6.93	0.34	3.73	11.83	54.16
C17	S	2	95	1.93	87.57	36.75	172.00	242.75	6.62	0.17	2.59	16.66	72.92
C18	LS	4	84	3.09	163.80	34.88	202.50	330.00	7.61	0.23	0.42	14.45	41.67
Mean		11	77	2.71	36.31	11.78	49.68	82.41	7.22	0.45	62.68	23.22	58.32

Table 2.2. Selected chemical and physical properties for the fine textured group of soils.

Soil Id	Texture	Clay	Sand	Carbonate	Olsen P	Water P	Modified Kelowna P	Mehlich 3 P	pH	Electrical Conductivity	Mehlich 3 Calcium	Mehlich 3 Magnesium	P150
		%			mg kg ⁻¹					ms cm ⁻¹	mmol kg ⁻¹		
Fine soils within range of Olsen P values for coarse textured group (<200 mg kg⁻¹)													
F1	HC	83	2	1.60	2.65	4.85	3.75	5.50	7.38	0.28	125.13	98.35	23.55
F2	CL	33	31	5.20	3.70	2.75	5.75	15.81	7.93	0.32	136.08	42.28	12.50
F3	CL	32	35	0	7.10	2.23	6.45	17.81	7.86	0.32	130.80	39.13	12.74
F4	CL	29	42	0.50	8.95	6.10	9.13	29.69	7.82	0.18	104.62	34.51	8.87
F5	CL	35	32	10.30	28.55	5.48	52.29	93.38	8.15	0.41	221.39	61.96	18.95
F6	CL	32	26	0.10	31.80	12.20	31.38	63.44	7.39	0.36	103.31	37.23	10.89
F7	CL	28	40	0.60	35.95	15.50	44.12	74.88	6.32	0.15	97.83	21.25	9.68
F8	HC	74	4	0.50	35.95	7.60	37.71	57.38	7.60	0.40	114.40	101.73	19.03
F9	CL	33	34	0.20	46.65	28.38	48.42	101.25	7.66	0.43	112.19	45.96	8.23
F10	SCL	27	48	0.00	53.50	14.78	68.58	97.56	7.83	0.31	118.74	37.66	12.58
F11	CL	30	42	3.00	58.10	12.88	51.29	112.88	7.91	0.34	153.80	37.26	11.37
F12	HC	72	8	1.10	67.37	8.71	67.50	93.75	6.92	0.53	8.55	15.87	495.83
F13	HC	74	5	1.10	81.13	5.13	56.63	92.63	6.70	0.47	7.57	28.59	710.42
F14	SCL	26	53	13.40	84.85	22.63	130.00	186.75	8.05	1.09	120.46	88.48	13.06
F15	HC	64	2	0	102.70	29.35	110.50	183.50	7.69	0.36	118.89	103.34	17.10
F16	CL	38	43	0.44	106.30	24.29	138.00	202.38	7.27	0.86	5.21	17.61	385.42
F17	HC	75	5	0.77	128.47	10.38	116.50	177.88	6.82	1.26	7.75	23.14	550.00
F18	SCL	29	45	1.30	140.95	45.06	164.38	306.75	7.84	0.37	130.17	42.32	9.03
F19	HC	70	7	0.52	156.95	20.50	128.63	214.00	6.69	0.77	6.29	27.58	491.67
F20	CL	39	30	27.30	170.93	45.80	279.50	326.75	8.03	0.38	221.89	77.73	16.29
Mean		46	27	3.40	67.63	16.23	77.52	122.70	7.49	0.48	102.25	49.10	141.86
Fine soils beyond range of Olsen P values for coarse textured group (>200 mg kg⁻¹)													
F21	HC	77	5	1.60	254.80	72.25	232.88	338.00	7.70	0.45	132.90	104.39	15.97
F22	C	52	14	2.45	302.00	86.00	323.50	363.25	7.76	0.71	7.57	28.59	268.75

Table 2.3. Linear regression for concentration of total dissolved P (TDP) in runoff with all methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the first 30 minutes of runoff from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.0327 a	0.0371	0.93 ***	<0.0001	0.0240 a	0.2642	0.52 ***	0.0004	0.0283	0.1453	0.67 ***	<0.0001
Olsen (Ols-P)	0.0076 a†	0.1450	0.72 ***	<0.0001	0.0073 a	0.1632	0.77 ***	<0.0001	0.0074	0.1539	0.77 ***	<0.0001
Modified Kelowna (MK-P)	0.0059 a	0.1308	0.85 ***	<0.0001	0.0048 a	0.2787	0.58 ***	0.0001	0.0054	0.1971	0.70 ***	<0.0001
Mehlich 3 (M3-P)	0.0038 a	0.1089	0.80 ***	<0.0001	0.0039 a	0.1758	0.68 ***	<0.0001	0.0040	0.1349	0.74 ***	<0.0001
Ols-P/(P150)	0.0133 a	0.2413	0.60 ***	0.0001	0.0480 b	0.2291	0.64 ***	<0.0001	0.0156	0.3713	0.35 ***	<0.0001
M3-P/(P150)	0.0067 a	0.2187	0.69 ***	<0.0001	0.0235 b	0.2684	0.53 ***	0.0003	0.0071	0.3817	0.32 ***	0.0002
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0133 a§	0.2513	0.51 **	0.0020	0.0106 a	0.4784	0.32 **	0.0093	0.0081 ¶	0.3961	0.32 ***	0.0004
M3-P/M3(Ca+Mg)α ₁	0.0039 a§	0.2272	0.59 ***	0.0005	0.0084 a	0.4387	0.38 **	0.0036	0.0041 ¶	0.4030	0.29 ***	0.0006
Ols-P/((2xP150)+Ols-P)	0.0170 a	0.1778	0.72 ***	<0.0001	0.0702 b	0.1551	0.73 ***	<0.0001	0.0184	0.3612	0.35 ***	0.0001
M3-P/((2xP150)+M3-P)	0.0143 a	0.0973	0.83 ***	<0.0001	0.0390 b	0.1792	0.60 ***	<0.0001	0.0142	0.3104	0.38 ***	<0.0001
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0132 a§	0.1516	0.68 ***	<0.0001	0.0133 a	0.4091	0.37 **	0.0043	0.0130 ¶	0.3006	0.44 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0112 a§	0.0810	0.74 ***	<0.0001	0.0138 a	0.3031	0.48 ***	0.0007	0.0116 ¶	0.2285	0.49 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0100 a‡‡	0.1658	0.73 ***	<0.0001	0.0344 b	0.1311	0.75 ***	<0.0001	0.0118 §§	0.3146	0.40 ***	<0.0001
WEP/(PSI+WEP) ††	0.0138 a‡‡	0.2068	0.77 ***	<0.0001	0.0610 b	0.3647	0.37 **	0.0042	0.0123 §§	0.4262	0.23 **	0.0026
MK-P/(PSI+MK-P) ††	0.0097 a‡‡	0.1510	0.73 ***	<0.0001	0.0275 b	0.1945	0.65 ***	<0.0001	0.0111 §§	0.3067	0.39 ***	<0.0001
M3-P/(PSI+M3-P) ††	0.0097 a‡‡	0.0895	0.72 ***	<0.0001	0.0233 b	0.0982	0.67 ***	<0.0001	0.0114 §§	0.2226	0.44 ***	<0.0001

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

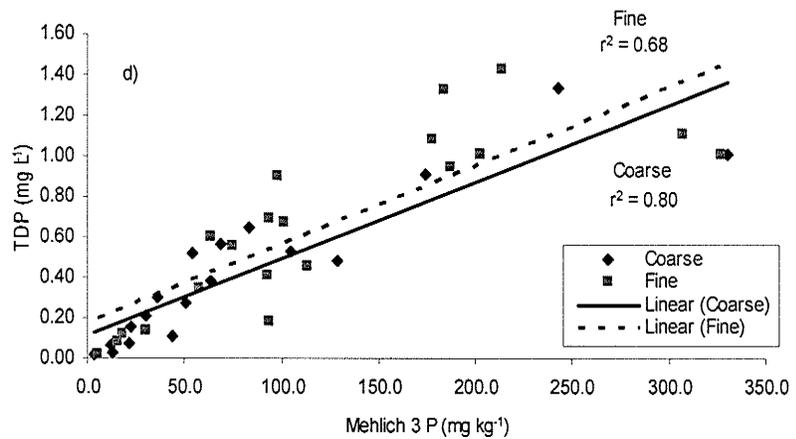
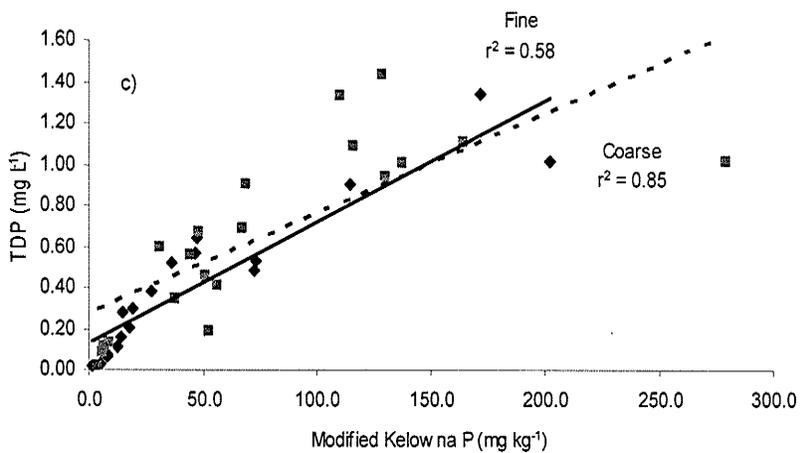
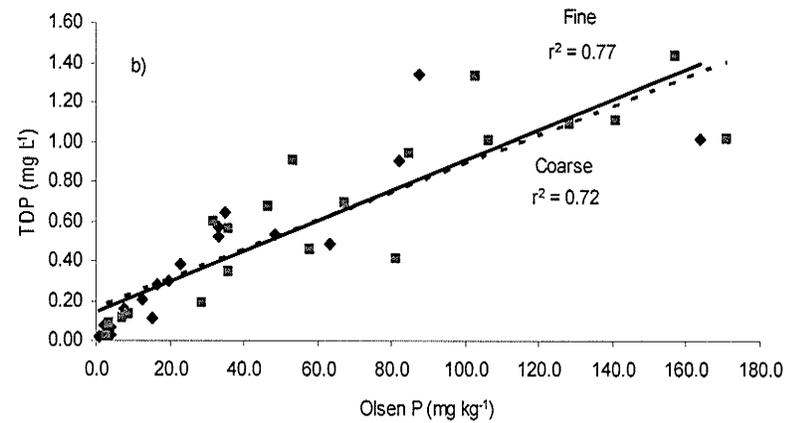
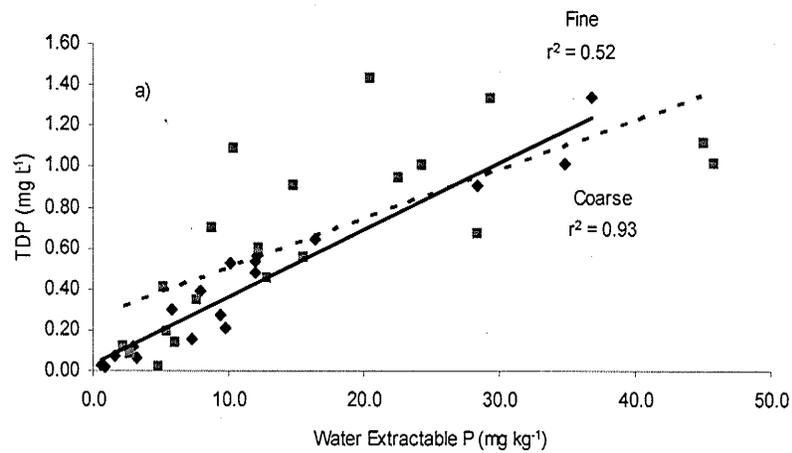


Fig 2.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in the first 30 minutes of runoff.

Among the agronomic soil tests for P, the relationship between Ols-P and TDP in runoff was strong and consistent across both textural groups and for all soils combined (Table 2.3, Fig. 2.1b). The linear equations for the textural groups have slopes that are not significantly different from each other ($p < 0.05$). The y intercepts for both linear equations are similar and slightly greater than zero, indicating that these equations probably over predict runoff loss at low Ols-P. Nonetheless, these regression equations show that TDP concentrations in runoff are similar for coarse and fine textured soils that have similar Ols-P values.

All of the STP methods that were examined in our study had strong relationships and were able to predict TDP quite well in the coarse textured group; the relationships were weaker with the fine textured soils but still predicted TDP reasonably well with r^2 values ranging from 0.52 (WEP) to 0.77 (Ols-P) (Table 2.3, Fig. 2.1b). This contradicts results from other studies where soils behaved so differently that one STP threshold did not suit all soils (McDowell et al., 2000). Overall, in the coarse textured soils the ranking of STP methods for predicting TDP in runoff water were WEP > MK-P > M3-P > Ols-P (Table 2.3). For the fine textured and all soils combined there was a reversal in the ability to predict TDP losses, with Ols-P > M3-P > MK-P > WEP (Table 2.3, Fig. 2.1).

The typical environmental STP method of WEP outperformed the agronomic methods in the coarse textured soils because a relatively larger proportion of the P in these soils is readily water soluble and available to mild extraction methods (Kumaragamage et al., 2008). Fine textured soils have more P in less labile pools that are extracted from soil particles by more aggressive extraction solutions. The surface of these fine soils also interacts intensively with the runoff water due to the shallow EDI

that the fine textures exhibit. This intensive displacement of soil solution in the surface of fine textured soils forces the surface soil to replenish the soil solution with additional P from the less water soluble but still labile pools. Since agronomic STP methods measure the quantity of labile P as well as the intensity of the water soluble P (Kumaragamage et al., 2008; McDowell and Sharpley, 2003), these methods may be well suited for measuring the risk of TDP loss from fine textured soils.

Many other researchers have also found very good correlations between typical agronomic soil STP methods and SRP or TDP concentrations in runoff water (Little et al., 2007; Pautler and Sims, 2002; Pote et al., 1996; Schroeder et al., 2004; Vadas et al., 2005; Wright et al., 2006; Wright et al., 2003). However, some researchers have suggested that although STP is a good indicator for potential loss within a group of similar soils, it cannot be relied on for many soils of different physical and chemical composition (Sharpley, 1995). Due to this problem, the concept of degree of P saturation (DPS) has been conceived and applied successfully in other studies.

Equations for $DPS_{(P150)}$ and $DPS_{(M3CaMg)}$ were used with either Ols-P or M3-P as the STP value in the numerator (Ige et al., 2005a,b) and the numerator and denominator in $DPS_{(P150+STP)}$ and $DPS_{(M3CaMg+STP)}$ (Akinremi et al., 2007). In addition, equation $DPS_{(PSI+STP)}$ used Ols-P, WEP, MK-P, and M3-P values in the numerator and denominator (Casson et al., 2006), for a total of twelve DPS methods evaluated. As with simpler STP methods, the DPS methods were more strongly related to runoff TDP concentrations from coarse textured soils than from fine textured soils (Table 2.3, Figs. 2.2 and 2.3). This may be due to the physical properties that allow fine textured soils to retain P. Phosphorus retention and release in Manitoba soils rely more on the quantity of

clay in the soil in addition to chemical characteristics such as extractable Ca and Mg (Ige et al., 2005b). Conversely, in a similar study with American soils, Kleinman and Sharpley (2002) found that with a similar method of determining DPS that adding clay content did not significantly improve the relationship.

In our study the only situation where a DPS method outperformed Ols-P was when $DPS_{(P150+STP)}$ and $DPS_{(M3CaMg+STP)}$ were calculated with M3-P as the STP input within the coarse textured group (Table 2.3). However, even in these cases the regression relationships between $DPS_{(P150+STP)}$ and $DPS_{(M3CaMg+STP)}$ were only slightly better than Ols-P alone and less strongly related than simple STP methods with TDP losses from fine textured soils or all the soils grouped together. Degree of P saturation calculations were meant to eliminate the need to further divide soils and account for the ability of any particular soil to retain P. However, in our study when all soils are grouped together, the relationship of DPS to TDP was not as strong as the simple STP methods (Table 2.3, Figs. 2.2 and 2.3). For example, the slopes of the linear regressions for each textural group were significantly different ($p < 0.05$) with any method that used the P150 isotherm to estimate PSC. When using Mehlich extractable Ca + Mg to estimate PSC, the slopes between the coarse and fine groups were not significantly different; however, the r^2 values for the relationship between DPS and TDP in runoff from the fine textured group ranged from 0.37** using Ols-P in equation $DPS_{(M3Ca+Mg)}$ to a high of only $r^2 = 0.48^{***}$ using M3-P in equation $DPS_{(M3CaMg+STP)}$. These relationships, although statistically significant, are too low to be used for prediction purposes, especially compared to those for Ols-P ($r^2 = 0.77^{***}$ for the fine soils and $r^2 = 0.72^{***}$ for the coarse soils).

One possible reason for the variability in DPS – TDP relationships across textural groups in our study may be the wide range of soil textures that were used in our study, ranging from 2% to 83% clay and 2 to 95% sand. This is a larger range than found in most other studies and this range of textures and depths of interaction with runoff water may have affected the ability of the DPS calculations to work consistently. McDowell et al. (2000) used soils from around the world with varying pH, STP and organic C but there is no mention of varying texture. In the study by McDowell et al. (2000) the soils behaved similarly, regardless of where in the world they came from, but McDowell et al. used a CaCl_2 extraction and not simulated rainfall to measure P availability for runoff. Vadas et al. (2005) compared six separate runoff studies and found that runoff SRP concentrations were more strongly related to DPS values than to STP. However, the studies examined by Vadas et al. (2005) were all conducted on non-calcareous soils with a range of soil textures (0.8 – 37% clay) that was narrower and coarser than soils used in our study.

2.3.3 Runoff Duration Effects

Runoff was collected for a total of 90 minutes of continuous runoff. A rainfall event of 75 mm hr^{-1} would rarely if ever occur for an entire 90 minutes in Manitoba; a 30 minute storm of this intensity is a 1 in 50 year event. However, snowmelt situations are much longer and the 90 minutes of runoff may provide insight into how the release of P changes over an extended time of extraction and how our ability to predict the P concentration may be affected.

As the rainfall event continued into the second time interval of 30-60 minutes of continuous runoff, the concentration of TDP in runoff from the soils decreased (Tables 2.3 and 2.4). As a result the slope for the relationship between STP or DPS and TDP declined an average of 26 to 44% for the fine and coarse soils respectively between the first and second time intervals. This was also observed by Wright et al. (2006) where the slopes at later time intervals were less than slope during the first 30 minutes of runoff. Presumably the most labile P was removed during the initial 30 minutes, leaving P that was increasingly less labile and therefore less likely to move quickly into runoff water. With our soils there was little change in STP – TDP relationships between the second and third interval (Tables 2.4, 2.5). Declining extraction coefficients were observed with all of the STP or DPS methods that were examined; however, the decline was less than for simple STP methods.

When flow weighted means for the entire 90 minute rainfall were analyzed, the extraction coefficients of all STP, DPS – TDP relationships were lower than for the first 30 minutes of collection (Table 2.3 and 2.6). Generally the r^2 values for the STP, DPS – TDP relationships also declined over the 90 minutes of rainfall, probably reflecting increasing variability expanded by differences in P buffering capacity among soils (Table 2.6). Among the simple soil tests, the r^2 values for the coarse textured soils over the entire 90 minute rainfall period varied from 0.69 for Ols-P to 0.86 for WEP both of which were lower than for the first 30 minutes (Tables 2.3 and 2.6). The r^2 values for fine textured soils also declined after the initial runoff period although the decline in r^2 values for Ols-P was less than for WEP, MK-P or M3-P (Tables 2.3, 2.4, 2.5, 2.6). Over the whole 90 minutes of runoff, Ols-P had the strongest relationship with TDP in runoff

when all soils were combined. The next strongest predictor of TDP over all collection periods was M3-P followed by MK-P then WEP (Table 2.6). All measures of DPS produced r^2 values that were lower than for simple STP methods (Table 2.6). Although these r^2 values for the DPS methods were statistically significant, the relationships were not strong enough for reliable prediction TDP in runoff.

2.3.4 Change Point

In the literature there has been a discussion of a “change point” for soil test P at which soils exhibit a change in the dynamics of P release to runoff, where the extraction coefficient makes an abrupt upward change. It is at this point that phosphorus is released much more easily for every unit of P increase in the soil (McDowell et al., 2000). This change point has been demonstrated with a variety of STP methods (McDowell et al., 2000; Hartz and Johnstone, 2005) as well as with different DPS methods (Maguire and Sims, 2002b; McDowell and Sharpley, 2001; McDowell et al., 2000; Nair et al., 2004; Casson et al., 2006). However, such a change point was not observed with any of the extraction methods in our study. In most studies where change points are noted, the change points are observed within a soil or a group of closely related soils. For example, McDowell et al. (2000) observed a change point with the Ols-P extraction in 14 of 18 soils but only in four with DPS calculated with oxalate P in a ratio with oxalate (Fe + Al) and three with the M3-P extraction, when the extraction methods were correlated with CaCl_2 extractable P. The pH of the soil may influence the change point behavior, and a soil may exhibit multiple change points depending on pH (McDowell et al., 2000).

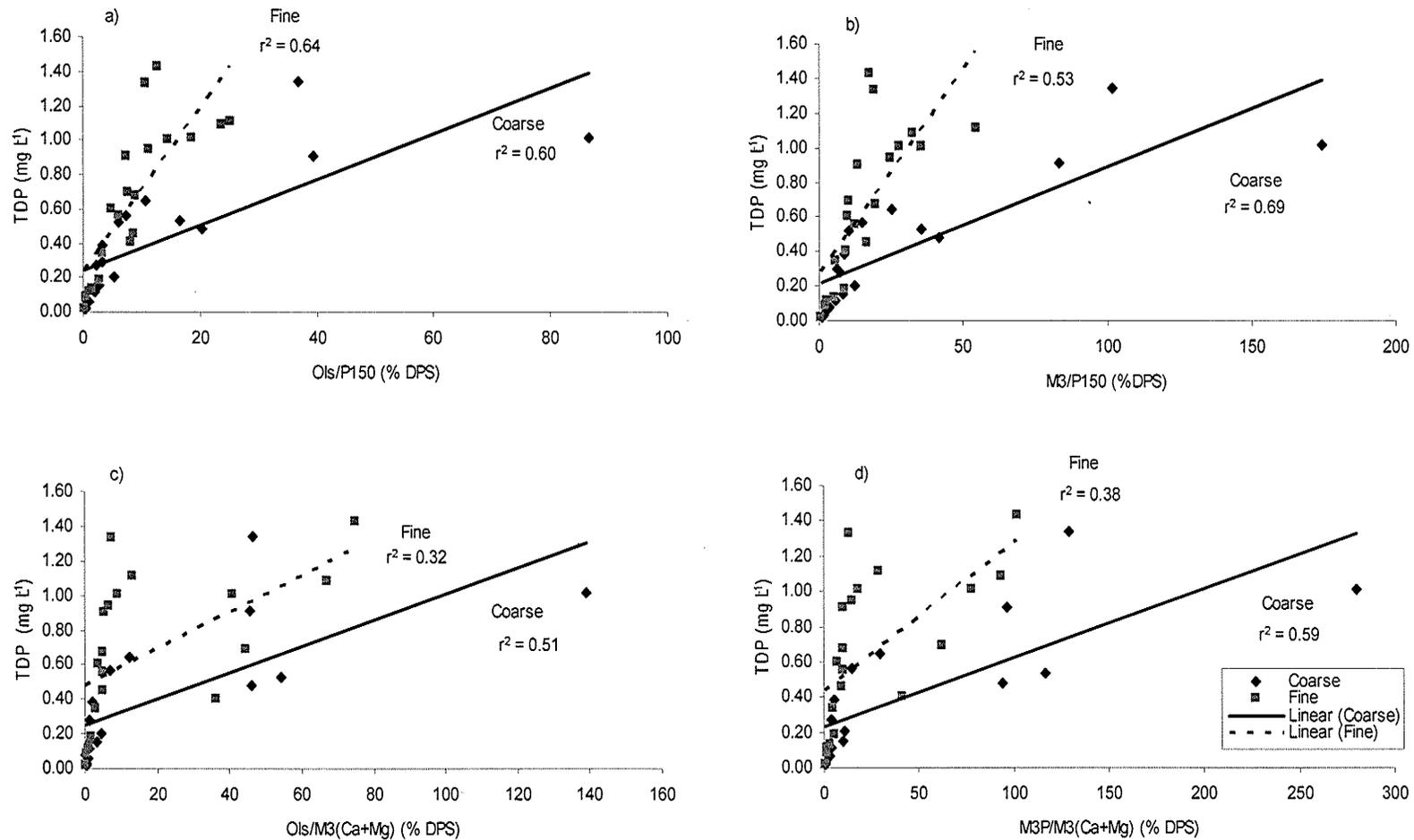


Fig 2.2. Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a,b) in the first 30 minutes of runoff.

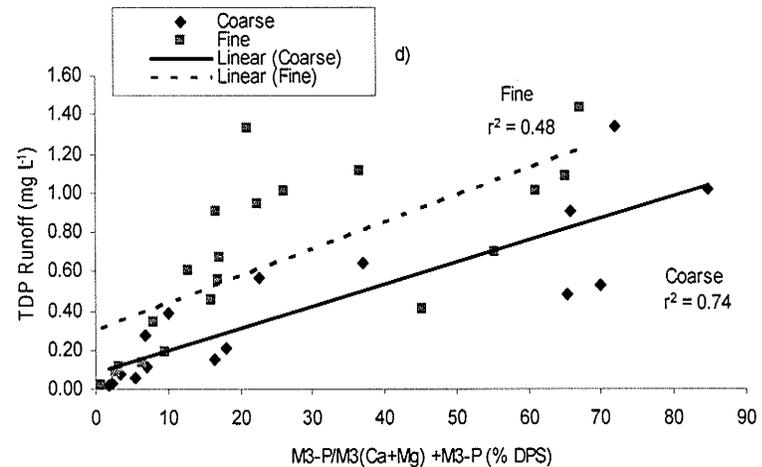
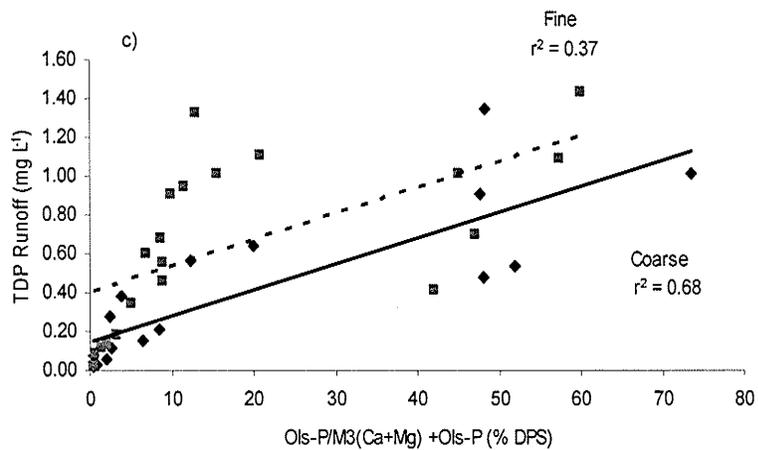
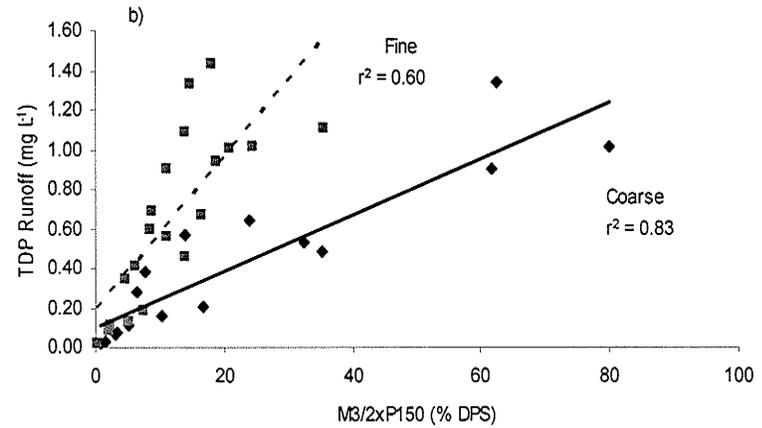
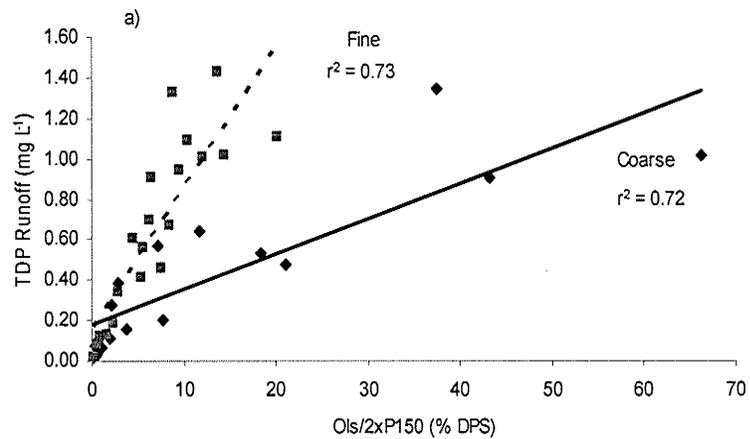


Fig 2.3. Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

Table 2.4 Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 30-60 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.0184 a	0.0770	0.80 ***	<0.0001	0.0152 a	0.2791	0.29 *	0.0140	0.0180	0.1655	0.43 ***	<0.0001
Olsen (Ols-P)	0.0045 a†	0.1305	0.68 ***	<0.0001	0.0060 a	0.1288	0.69 ***	<0.0001	0.0057	0.1203	0.71 ***	<0.0001
Modified Kelowna (MK-P)	0.0034 a	0.1265	0.76 ***	<0.0001	0.0037 a	0.2450	0.45 **	0.0012	0.0038	0.1741	0.55 ***	<0.0001
Mehlich 3 (M3-P)	0.0022 a	0.1139	0.72 ***	<0.0001	0.0029 a	0.0178	0.50 **	0.0011	0.0028	0.1344	0.57 ***	<0.0001
Ols-P/(P150)	0.0076 a	0.1892	0.54 ***	0.0005	0.0379 b	0.1973	0.53 ***	0.0003	0.0095	0.3136	0.20 ***	0.0045
M3-P/(P150)	0.0038 a	0.1783	0.59 ***	0.0002	0.0165 b	0.2634	0.34 **	0.0066	0.0039	0.3297	0.15 *	0.0157
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0048 a§	0.1571	0.60 ***	0.0007	0.0105 a	0.3776	0.45 **	0.0018	0.0061 ¶	0.3098	0.29 **	0.001
M3-P/M3(Ca+Mg)α ₁	0.0025 a§	0.1422	0.67 ***	0.0002	0.0077 a	0.3518	0.46 **	0.0014	0.0027 ¶	0.3298	.21 *	0.0068
Ols-P/((2xP150)+Ols-P)	0.0096 a	0.1667	0.61 ***	0.0001	0.0517 b	0.1657	0.53 ***	0.0003	0.0105	0.3152	0.18 **	0.0088
M3-P/((2xP150)+M3-P)	0.0078 a	0.1288	0.68 ***	<0.0001	0.0263 b	0.2121	0.36 **	0.0048	0.0078	0.2918	0.18 **	0.0089
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0080 a§	0.1217	0.68 ***	<0.0001	0.0129 a	0.2967	0.46 ***	0.0010	0.0099 ¶	0.2316	0.40 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0068 a§	0.0804	0.74 ***	<0.0001	0.0124 a	0.2166	0.52 ***	0.0004	0.0084 ¶	0.1898	0.40 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0058 a‡‡	0.1464	0.64 ***	0.0001	0.0252 b	0.1492	0.54 ***	0.0002	0.0071 §§	0.2838	0.22 **	0.0033
WEP/(PSI+WEP) ††	0.0075 ‡‡	0.1765	0.60 ***	0.0003	0.0339	0.3719	0.150	0.0871	0.0057 §§	0.3652	0.080	0.0939
MK-P/(PSI+MK-P) ††	0.0056 a‡‡	0.1365	0.65 ***	<0.0001	0.0192 b	0.2122	0.42 **	0.0020	0.0065 §§	0.2813	0.21 **	0.004
M3-P/(PSI+M3-P) ††	0.0057 a‡‡	0.0989	0.66 ***	<0.0001	0.0162 b	0.1465	0.43 **	0.0017	0.0069 §§	0.2273	0.25 **	0.0018

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table 2.5. Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 60-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.0181 a	0.0510	0.79 ***	<0.0001	0.0157 a	0.2322	0.28 *	0.0156	0.0178	0.1300	0.42 ***	<0.0001
Olsen (Ols-P)	0.0043 a†	0.1078	0.64 ***	<0.0001	0.0060 a	0.0820	0.67 ***	<0.0001	0.0056	0.0877	0.68 ***	<0.0001
Modified Kelowna (MK-P)	0.0034 a	0.0964	0.78 ***	<0.0001	0.0037 a	0.2012	0.43 ***	0.0017	0.0038	0.1385	0.53 ***	<0.0001
Mehlich 3 (M3-P)	0.0022 a	0.0847	0.73 ***	<0.0001	0.0029 a	0.1278	0.49 ***	0.0006	0.0027	0.0976	0.56 ***	<0.0001
Ols-P/(P150)	0.0073 a	0.1653	0.50 ***	0.0010	0.0350 b	0.1774	0.43 **	0.0016	0.0090	0.2820	0.18 *	0.0078
M3-P/(P150)	0.0037 a	0.1511	0.59 ***	0.0002	0.0153 b	0.2372	0.29 *	0.0154	0.0038	0.2942	0.15 *	0.0186
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0045 a§	0.1424	0.51 **	0.0027	0.0105 b	0.3288	0.43 **	0.0025	0.0059 ¶	0.2763	0.27 **	0.0015
M3-P/M3(Ca+Mg)α ₁	0.0024 a§	0.1253	0.61 ***	0.0006	0.0078 b	0.3024	0.44 **	0.0019	0.0027 ¶	0.2941	0.20 **	0.0077
Ols-P/((2xP150)+Ols-P)	0.0091 a	0.1463	0.56 ***	0.0004	0.0510 b	0.1251	0.49 ***	0.0006	0.0101	0.2816	0.16 *	0.0121
M3-P/((2xP150)+M3-P)	0.0074 a	0.1077	0.64 ***	<0.0001	0.0259 b	0.1719	0.34 *	0.0070	0.0075	0.2580	0.16 *	0.0113
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0075 a§	0.1058	0.60 ***	0.0004	0.0126 a	0.2551	0.43 **	0.0017	0.0095 ¶	0.2015	0.37 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0063 a§	0.0664	0.66 ***	0.0001	0.0122 a	0.1772	0.48 ***	0.0007	0.0081 ¶	0.1613	0.37 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0063 a‡‡	0.1162	0.72 ***	<0.0001	0.025 b	0.1083	0.50 ***	0.0005	0.0075 §§	0.2417	0.25 **	0.0017
WEP/(PSI+WEP) ††	0.0086 ‡‡	0.1410	0.77 ***	<0.0001	0.0331	0.3307	0.14	0.1036	0.0070 §§	0.3209	0.11 *	0.0411
MK-P/(PSI+MK-P) ††	0.006 a‡‡	0.1072	0.71 ***	<0.0001	0.0189 b	0.1722	0.39 **	0.0033	0.0069 §§	0.2402	0.23 **	0.0025
M3-P/(PSI+M3-P) ††	0.006 a‡‡	0.0700	0.70 ***	<0.0001	0.016 b	0.1072	0.40 **	0.0028	0.0072 §§	0.1867	0.26 **	0.0012

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table 2.6. Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.0231 a	0.0506	0.86 ***	<0.001	0.0181 a	0.2594	0.37 **	0.0047	0.0212	0.1455	0.52 ***	<0.0001
Olsen (Ols-P)	0.0055 a†	0.1237	0.69 ***	<0.0001	0.0063 a	0.1231	0.73 ***	<0.0001	0.0061	0.1178	0.75 ***	<0.0001
Modified Kelowna (MK-P)	0.0042 a	0.1122	0.82 ***	<0.0001	0.0040 a	0.2400 a	0.50 **	0.005	0.0043	0.1663	0.62 ***	<0.0001
Mehlich 3 (M3-P)	0.0027 a	0.0968	0.77 ***	<0.0001	0.0032 a	0.1596	0.58 ***	<0.0001	0.0031	0.1191	0.65 ***	<0.0001
Ols-P/(P150)	0.0094 a	0.196	0.56 ***	0.0004	0.0399 b	0.200	0.55 ***	0.0002	0.011	0.3190	0.25 **	0.0013
M3-P/(P150)	0.0050 a	0.179	0.64 ***	<0.0001	0.0181 b	0.256	0.39 **	0.0032	0.005	0.3310	0.21 **	0.0035
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0057 a§	0.1727	0.55 **	0.0017	0.0104 a	0.4010	0.41 **	0.0031	0.0067	0.3260 ¶	0.31 ***	0.0007
M3-P/M3(Ca+Mg)α ₁	0.0030 a§	0.1524	0.64 ***	0.0004	0.0078 a	0.3708	0.44 **	0.0019	0.0031	0.3413 ¶	0.25 **	0.0027
Ols-P/((2xP150)+Ols-P)	0.0118 a	0.1685	0.63 ***	<0.0001	0.0570 b	0.1486	0.60 ***	<0.0001	0.0129	0.3165	0.24 **	0.0020
M3-P/((2xP150)+M3-P)	0.0096 a	0.1202	0.71 ***	<0.0001	0.0300 b	0.1886	0.44 **	0.0014	0.0098	0.2840	0.25 **	0.0015
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0098 a§	0.1021	0.70 ***	<0.0001	0.013 a	0.3147	0.44 **	0.0014	0.0109	0.236 ¶	0.42 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0085 a§	0.0530	0.76 ***	<0.0001	0.0128 a	0.2272	0.52 ***	0.0004	0.0094	0.186 ¶	0.44 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0076 a‡‡	0.1376	0.72 ***	<0.0001	0.0279 b	0.1295	0.61 ***	<0.0001	0.0090	0.2743 §§	0.31 ***	0.0003
WEP/(PSI+WEP) ††	0.0103 a‡‡	0.1698	0.75 ***	<0.0001	0.0416 b	0.3559	0.22 *	0.0385	0.0087	0.3653 §§	0.16 *	0.0154
MK-P/(PSI+MK-P) ††	0.0073 a‡‡	0.1262	0.72 ***	<0.0001	0.0216 b	0.1928	0.50 ***	0.0005	0.0083	0.2704 §§	0.30 ***	0.0005
M3-P/(PSI+M3-P) ††	0.0073 a‡‡	0.0798	0.71 ***	<0.0001	0.0183 b	0.1183	0.51 ***	0.0004	0.0086	0.2063 §§	0.34 ***	0.0002

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Torbert et al. (2002) compared calcareous to non-calcareous soils and proposed that the free CaCO_3 present in calcareous soils may restrict the solubility of P at high STP levels.

2.3.5 Phosphorus Loading

Phosphorus concentration is only one way of evaluating the amount of phosphorus that is moving off of the landscape. Phosphorus loss can also be expressed as a quantity lost per unit area or phosphorus loading.

In our study the relationship between load and various STP and DPS methods followed trends similar to those for the concentration data. Among the simple STP methods Ols-P had the strongest linear relationships with TDP load for the coarse and fine textured soils during the first 30 minutes of runoff (Table 2.7) and during the entire 90 minute rainfall period (Table 2.8). Among the simple STP tests water extractable P was the most poorly related with TDP load for all soil groups and for both 0-30 minute and 0-90 minute collection intervals. Overall, however, the relationships between STP and TDP loads were weaker than those with TDP concentration data. This is consistent with research by Quinton et al. (2003) who observed strong relationships between runoff TDP concentrations and slightly weaker relationships when TDP load data were used.

The trend for the relationships between DPS and TDP load were also consistent with the concentration data, with DPS methods predicting the amount of TDP load more accurately in the coarse textured soils than in the fine textured soils during all collection periods. The methods that predicted TDP load most accurately were those with $M3(\text{Ca} + \text{Mg})$ in the denominator. However, all of the DPS regressions with TDP load were significantly different ($p < 0.05$) across textures so one DPS equation cannot be used for

Table 2.7. Linear regression for total dissolved P (TDP) load per tray in runoff with all methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the first 30 minutes of rainfall (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.249 a	2.859	0.23 *	0.0437	0.359 a	5.415	0.35 *	0.0059	0.347	3.750	0.33 ***	0.0002
Olsen (Ols-P)	0.099 a†	2.181	0.52 ***	0.0007	0.126 a	0.237	0.70 ***	<0.0001	0.122	2.21	0.67 ***	<0.0001
Modified Kelowna (MK-P)	0.059 a	2.852	0.37 **	0.0073	0.078 a	5.165	0.46 **	0.0010	0.077	3.720	0.45 ***	<0.0001
Mehlich 3 (M3-P)	0.042 a	2.332	0.42 **	0.0037	0.065 a	3.213	0.58 ***	<0.0001	0.059	2.551	0.53 ***	<0.0001
Ols-P/(P150)	0.174 a	3.146	0.43 *	0.0056	0.916 b	3.126	0.70 ***	<0.0001	0.216	6.300	0.22 **	0.0044
M3-P/(P150)	0.077 a	3.165	0.37 *	0.0120	0.436 b	4.104	0.55 ***	0.0002	0.082	6.826	0.14 *	0.0266
Ols-P/M3(Ca+Mg) α_1 ‡	0.128 a§	2.785	0.61 ***	0.0003	0.241 b	7.257	0.50 ***	0.0005	0.153 ¶	5.818	0.37 ***	<0.0001
M3-P/M3(Ca+Mg) α_1	0.059 a§	2.728	0.57 ***	0.0007	0.189 b	6.381	0.59 ***	<0.0001	0.068 ¶	6.280	0.27 **	0.0013
Ols-P/((2xP150)+Ols-P)	0.195 a	2.937	0.39 *	0.0101	1.252 b	2.345	0.71 ***	<0.0001	0.215	6.578	0.15 *	0.0193
M3-P/((2xP150)+M3-P)	0.146 a	2.372	0.37 *	0.0132	0.686 b	2.887	0.57 ***	0.0001	0.153	6.181	0.14 *	0.0250
Ols-P/(M3(Ca+Mg) α_2 + Ols-P) #	0.190 a§	1.784	0.60 ***	0.0005	0.295 b	5.808	0.56 ***	0.0002	0.231 ¶	4.301	0.44 ***	<0.0001
M3-P/(M3(Ca+Mg) α_2 + M3-P)	0.147 a§	1.19	0.54 **	0.0011	0.297 b	3.658	0.68 ***	<0.0001	0.194 ¶	3.394	0.43	<0.0001
Ols-P/(PSI+Ols-P) ††	0.128 a‡‡	2.729	0.45 *	0.0063	0.624 b	1.760	0.75 ***	<0.0001	0.162 §§	5.835	0.24 **	0.0030
WEP/(PSI+WEP) ††	0.104 a‡‡	4.274	0.17	0.1309	1.011 b	6.441	0.31 *	0.0104	0.079 §§	8.197	0.03	0.3157
MK-P/(PSI+MK-P) ††	0.127 a‡‡	2.403	0.48 **	0.0045	0.481 b	3.201	0.60 ***	<0.0001	0.152 §§	5.709	0.23 **	0.0033
M3-P/(PSI+M3-P) ††	0.135 a‡‡	1.338	0.53 **	0.0021	0.419 b	1.260	0.65 ***	<0.0001	0.169 §§	4.214	0.30 ***	0.0006

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p<0.05

‡ $\alpha_1 = 0.2$

§ n=16

¶ n=36

$\alpha_2 = 0.1$

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table 2.8. Linear regression for total dissolved P (TDP) load per tray in runoff with all methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the entire 90 minutes of rainfall (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.515	8.080	0.187	0.0728	0.931	16.179	0.268 *	0.0194	0.875	10.803	0.260 **	0.0011
Olsen (Ols-P)	0.213 a†	6.402	0.458 **	0.0020	0.369 a	6.340	0.684 ***	<0.0001	0.337	5.365	0.642 ***	<0.0001
Modified Kelowna (MK-P)	0.125 a	7.943	0.313 *	0.0157	0.218 a	14.400	0.404 **	0.0026	0.202	10.188	0.39 ***	<0.0001
Mehlich 3 (M3-P)	0.088 a	6.871	0.352 *	0.0095	0.181 a	9.106	0.506 ***	0.0004	0.154	7.243	0.451 ***	0.0001
Ols-P/(P150)	0.372 a	8.181	0.381 *	0.0109	2.489 b	9.237	0.590 ***	<0.0001	0.487	17.859	0.136 *	0.0269
M3-P/(P150)	0.163 a	8.276	0.321 *	0.0222	1.106 b	13.171	0.403 **	0.0027	0.167	19.460	0.071	0.1161
Ols-P/M3(Ca+Mg) α_1 ‡	0.280 a§	7.260	0.564 ***	0.0008	0.754 b	18.835	0.556 ***	0.0002	0.399 ¶	15.735	0.309 ***	0.0004
M3-P/M3(Ca+Mg) α_1	0.129 a§	7.163	0.519 **	0.0016	0.566 b	16.734	0.605 ***	<0.0001	0.165 ¶	17.420	0.192 *	0.0074
Ols-P/((2xP150)+Ols-P)	0.418 a	7.735	0.340 *	0.0178	3.379 b	7.283	0.584 ***	<0.0001	0.461	18.730	0.087	0.0816
M3-P/((2xP150)+M3-P)	0.311 a	6.534	0.319 *	0.0225	1.749 b	9.981	0.417 **	0.0021	0.315	18.114	0.073	0.1101
Ols-P/(M3(Ca+Mg) α_2 + Ols-P) #	0.419 a§	5.018	0.554 ***	0.0009	0.883 b	15.034	0.567 ***	0.0001	0.609 ¶	11.653	0.384 ***	<0.0001
M3-P/(M3(Ca+Mg) α_2 + M3-P)	0.324 a§	3.719	0.506 **	0.0020	0.859 b	9.392	0.643 ***	<0.0001	0.496 ¶	9.668	0.354 ***	0.0001
Ols-P/(PSI+Ols-P) ††	0.271 a‡‡	7.313	0.388 *	0.0131	1.668 b	5.943	0.607 ***	<0.0001	0.361 §§	16.943	0.148 *	0.0226
WEP/(PSI+WEP) ††	0.207 ‡‡	10.804	0.127	0.1925	2.309	20.331	0.185	0.0584	0.108 §§	22.842	0.007	0.6288
MK-P/(PSI+MK-P) ††	0.274 a‡‡	6.546	0.420 *	0.0090	1.236 b	10.633	0.451 **	0.0012	0.333 §§	16.814	0.139 *	0.0271
M3-P/(PSI+M3-P) ††	0.292 a‡‡	4.207	0.472 **	0.0047	1.077 b	5.619	0.491 ***	0.0006	0.379 §§	13.278	0.190 *	0.0089

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p<0.05

‡ $\alpha_1 = 0.2$

§ n=16

¶ n=36

$\alpha_2 = 0.1$

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

all soils. Also, all of the r^2 values for TDP load – DPS relationships were weaker than for Ols-P, MK-P and M3-P when all soils were grouped together.

2.4.0 Summary and Conclusions

Olsen-P was the most reliable soil test method for predicting the concentration of TDP in runoff water from Manitoba soils across coarse and fine soil textures and for the entire runoff period. Several of the DPS methods that have been developed for neutral to alkaline soils were able to predict TDP concentrations reasonably well within a textural group and maintained their ability to predict TDP concentrations in runoff over the entire 90 minutes of rainfall. However, these equations were not strongly related to runoff TDP concentrations when coarse and fine soils were combined and treated as a single group, even though it is in these situations that DPS was expected to excel.

The Ols-P method was also able to predict P runoff loads most consistently across textural groups and for the entire duration of the rainfall event. The correlations with the load data were not as strong as with concentration data, but the conclusions were the same. The correlations between load and DPS values followed the same trend as the concentration data, with DPS predicting runoff P losses reasonably well within textural groups but not when all the soils were considered together. Therefore, more work is needed to be done to account for differences in DPS – TDP relationships between soil textural groups.

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Dissolved Phosphorus Lost from Manitoba Soils in Percolate from Simulated Rainfall

3.0 Abstract

Percolating water may carry environmentally significant quantities of phosphorus (P) to groundwater, which can then carry this P to surface water, increasing the risk of eutrophication. We used 39 soils from agricultural Manitoba where percolate water was collected from packed soil boxes placed on a table with a 5% slope and exposed to 75 mm hr⁻¹ of simulated rainfall for 90 minutes of continuous runoff. Our study used Olsen (sodium bicarbonate), water extractable, Mehlich 3, Modified Kelowna soil test P (STP) methods. Several methods of degree of P saturation (DPS) were also evaluated, using extractable Ca and Mg or single point adsorption isotherms to estimate phosphorus sorption capacity (PSC) and related those measures of soil P with the total dissolved P (TDP) that percolated through the soil during the rainfall simulation experiments. Among the simple soil tests, water extractable P was the most accurate predictor of TDP in the percolate within textural groups for both concentration ($r^2=0.57$ and 0.65 coarse and fine textured soils, respectively) and load ($r^2=0.32$ and 0.48 for coarse and fine soils, respectively). For predicting TDP concentrations and loads the DPS methods were stronger than the simple STP methods, especially the DPS methods with single point adsorption isotherms where water or Mehlich 3 were used in both numerator and denominator.

3.1 Introduction

The quantities of phosphorus (P) that may leach through the soil profile are agronomically insignificant, but may be significant environmentally (Turner and Haygarth, 2000). In the past it has been generally accepted that P deficient subsoils would be able to intercept any P movement downward (Turner and Haygarth, 2000). However, the risk of P moving in subsurface flow may be increasingly important as more producers move toward tile draining lands to make the land available to more valuable crops such as potatoes or for ethanol production, especially in coarse textured soils or soils with large cracks which would allow for preferential flow (Sims et al., 1998; Turner and Haygarth, 2000).

Phosphorus leaching studies have been conducted using various methods of determining soil test P (STP) or degree of phosphorus saturation (DPS) to predict P leaching losses. Many of these studies have used either existing tile drains, lysimeters or intact or packed columns with the leachate correlated to different methods of measuring P in soil (Hartz and Johnstone, 2005; Heckrath et al., 1995; Hesketh and Brookes, 2000; Maguire and Sims 2002a, b; McDowell and Sharpley, 2001; Nelson et al., 2005; Turner and Haygarth, 2000). For example, Maguire and Sims (2002a, b) used Mehlich 3 P (M3-P) as well as DPS methods using M3-P/M3(Fe+Al) to predict leachate losses from packed soil columns. These researchers determined a change point at which the amount total dissolved P (TDP) in percolate water increased rapidly with a small increase in STP or DPS. Hartz and Johnstone (2005) also determined that P in leachate collected from packed soil columns was strongly related with typical environmental and agronomic soil test methods, such as Olsen P (Ols-P), CaCl_2 - P and a DPS method using the ratio of

Ols-P to the phosphorus saturation index (PSI) determined with a solution of 0.01M CaCl_2 containing 15 mg L^{-1} P provided from KH_2PO_4 . All of these methods predicted P lost through leaching and the DPS method showed change point behaviour.

McDowell and Sharpley (2001) used lysimeters to collect leachate water from the top 30 cm of the soil and correlated soluble reactive P (SRP) to different STP methods. Water extractable P (WEP) and CaCl_2 -P produced strong relationships in the two soils that were examined. Hesketh and Brooks (2000) also used lysimeters and found strong relationships that exhibited change points with Ols-P and CaCl_2 - P, but they cautioned about applying this lysimeter data to field situations. Field studies have been conducted by Heckrath et al. (1995) and Nelson et al. (2005) to look at relationships between soil P concentration and the P concentration in leachate. Nelson et al. (2006) studied unsaturated flow in soils and found DPS, determined by the ratio of oxalate P with oxalate Fe + Al, showed a strong split line relationship with a change point at 45% saturation. Heckrath et al. (1995) compared Ols-P in soil to SRP in drainage water from tile drains and found a change point at 60 mg kg^{-1} . However, no research has been conducted on the relationship between soil and percolate P in Manitoba soils.

Therefore, our study was designed to explore the relationship between soil and percolate P for 38 soils collected from across agricultural Manitoba. The specific objectives of this experiment were to: (1) determine what simple STP method (Olsen, Mehlich-3, WEP, or Modified Kelowna) would be the most reliable predictor of percolate TDP, (2) determine if the DPS methods developed for calcareous soils (Ige et al., 2005a, b; Akinremi et al., 2007; Casson et al., 2006) could predict TDP in percolate across a variety of soils.

3.2.0 Materials and Methods

3.2.1 Soil Collection

Soil collection and analytical procedures are described in detail in the previous chapter titled: Dissolved Phosphorus Concentrations and Loads Lost from Manitoba Soils under Simulated Rainfall.

3.2.2 Degree of Phosphorus Saturation

Five DPS formulas were used in this study, including four DPS formulas that have been developed for Manitoba soils (equations 1-4) and one for Alberta (equation 5) as follows:

$$[1] \text{ DPS}_{(P150)} \quad (\%) = \frac{STP}{P150} \times 100 \quad (\text{Ige et al., 2005a})$$

$$[2] \text{ DPS}_{(M3CaMg)} \quad (\%) = \frac{STP}{\alpha (Ca_{M3} + Mg_{M3})} \times 100 \quad (\text{Ige et al., 2005b})$$

$$\alpha = 0.2$$

$$[3] \text{ DPS}_{(P150+STP)} \quad (\%) = \frac{STP}{(2 \times P150) + STP} \times 100 \quad (\text{Akinremi et al., 2007})$$

$$[4] \text{ DPS}_{(M3CaMg+STP)} \quad (\%) = \frac{STP}{\alpha (Ca_{M3} + Mg_{M3}) + STP} \times 100 \quad (\text{Akinremi et al., 2007})$$

$$\alpha = 0.1$$

$$[5] \text{ DPS}_{(PSI+STP)} \quad (\%) = \frac{STP}{(PSI + STP)} \times 100 \quad (\text{Casson et al., 2006})$$

The STP methods used in equations 1-4 were Ols-P and M3-P; in equation 5 all STP methods were evaluated. Measures of P sorption capacity (PSC) included the P sorption maximum estimated from a P150 adsorption isotherm (P150) (Ige et al., 2005a). Mehlich 3 extractable Ca and Mg ($Ca_{M3}+Mg_{M3}$) was also used to estimate PSC because Ca and Mg are largely responsible for P retention in calcareous soils (Akinremi et al., 2007; Ige et al., 2005b). Following the research by Casson et al. (2006) in Alberta, PSC was also estimated using the phosphorus sorption index (PSI) determined using a $CaCl_2$ solution containing 75 mg P L^{-1} as KH_2PO_4 (Bache and Williams, 1971) and then calculated as:

$$[6] \quad \text{PSI (mg kg}^{-1}\text{)} = \frac{XV}{S}$$

where X = initial – final solution P (mg L^{-1}), V is the volume of the solution (L), and S is the soil mass (kg) (Casson et al., 2006).

3.2.3 Rainfall Simulator and Runoff/Percolate Collection Procedures

The rainfall simulator and procedures for collecting runoff and percolate from soil trays are described in the previous chapter titled: Dissolved Phosphorus Concentrations and Loads Lost from Manitoba Soils under Simulated Rainfall.

3.2.4 Statistical Analysis

Simple linear regression analysis was performed as well as a test for homogeneity between the soil groups within a STP method using the PROC GLM function within SAS version 9.1 (SAS Institute, Cary, NC).

3.3.0 Results and Discussion

The soils collected were divided into two textural groups based on percent clay content: a coarse textured group (< 25% clay) and a fine textured group (>26% clay) (Brady and Weil, 2008). The mean clay content for the coarse textured group was 10% and for the fine textured group 49% (Tables 2.1 and 2.2). Due to differences in infiltration rates, the runoff volumes that were obtained from each textural group varied. The fine soils produced a mean runoff of 85% of the total rainfall collected; the coarse soils produced a mean runoff of 77% of the total. The remaining water was collected as percolate and therefore had more contact with the soil than runoff water.

The majority of the phosphorus (P) present in the percolate water from the packed soil boxes was in the form of dissolved P (<0.45 μm). For the coarse soils, dissolved P accounted for 60% of the total P (TP) in percolate; for the fine soils, dissolved P comprised 68% of the TP in percolate. The high proportion of DP in percolate was partly due to the soil boxes being lined with a fine landscaping fabric that retained soil in the trays but allowed water through. As a result of the way that the boxes were lined, these particulate P (PP) data are not realistic for field conditions; therefore, only the TDP data will be discussed for percolate data.

Water extractable P (WEP) was the best predictor of TDP in the percolate water accounting for approximately 60% of the variation within each textural group, but only 30% of variation in TDP when data for all soils were grouped together (Table 3.1). Common STP methods (Ols-P, MK-P and M3-P) were poorly related to percolate TDP ($r^2 < 0.2$). This is not consistent with the findings of Maguire and Sims (2002a, b) who

Table 3.1. Linear regression for total dissolved P (TDP) concentrations in percolate with all methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the entire 90 minutes of rainfall from soils with Olsen P concentrations <200 mg kg⁻¹ (n=16 coarse group, n=20 fine group).

STP or DPS	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.3679 a	-0.9354	0.57 ***	0.0007	0.0818 b	0.2375	0.65 ***	<0.0001	0.1735	-0.0510	0.30 ***	0.0006
Olsen (Ols-P)	0.0595 a†	1.3406	0.22	0.0707	0.0149 b	0.5552	0.35 **	0.0057	0.0219	1.2673	0.08	0.0974
Modified Kelowna (MK-P)	0.0551 a	0.6871	0.36 *	0.0135	0.0112 b	0.6976	0.34 **	0.0073	0.0244	0.8419	0.16 *	0.0142
Mehlich 3 (M3-P)	0.0332 a	0.6861	0.30 *	0.0298	0.0099 b	0.3504	0.48 ***	0.0007	0.0173	0.6100	0.16 *	0.0142
Ols-P/(P150)	0.1084	1.9825	0.19	0.0876	0.1183	0.5166	0.42 **	0.002	0.1173	1.1151	0.23 **	0.003
M3-P/(P150)	0.0608 a	1.5650	0.27 *	0.0392	0.0723 a	0.3812	0.54 ***	0.0002	0.0655	0.9013	0.32 ***	0.0003
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0427 ‡	2.6000	0.08	0.2921	0.0064	1.4600	0.01	0.6382	0.034 ††	1.8013	0.07	0.1304
M3-P/M3(Ca+Mg)α ₁	0.0257 ‡	2.2903	0.12	0.1842	0.0079	1.1361	0.04	0.4148	0.0253 ††	1.5360	0.13 *	0.029
Ols-P/((2xP150)+Ols-P)	0.169 a	1.1872	0.33 *	0.0192	0.1988 a	0.1527	0.64 ***	<0.0001	0.1793	0.6247	0.39 ***	<0.0001
M3-P/((2xP150)+M3-P)	0.1504 a	0.1433	0.45 **	0.0047	0.1275 a	0.0121	0.70 ***	<0.0001	0.1510	-0.0939	0.49 ***	<0.0001
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.1095 ‡	1.3240	0.23	0.0625	0.0131	1.3232	0.04	0.4007	0.0677 ††	1.1470	0.14 **	0.025
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.1022 ‡	0.4482	0.30 *	0.0277	0.0195	1.0690	0.10	0.1652	0.0726 ††	0.4423	0.22 **	0.0037
Ols-P/(Ols-P+PSI) ††	0.0800 a§	0.7267	0.35 *	0.0213	0.0937 a	0.1422	0.60 ***	<0.0001	0.0834 ††	0.4468	0.39 ***	<0.0001
WEP/(WEP+PSI) ††	0.1433 a§	0.5315	0.62 ***	0.0005	0.2549 a	0.3561	0.71 ***	<0.0001	0.1442 ††	0.7252	0.62 ***	<0.0001
MK-P/(MK-P+PSI) ††	0.0768 a§	0.6050	0.34 *	0.023	0.0786 a	0.2510	0.58 ***	0.0001	0.0785 ††	0.3843	0.38 ***	<0.0001
M3-P/(M3-P+PSI) ††	0.0740 a§	0.2116	0.31 *	0.0311	0.0708 a	-0.1220	0.67 ***	<0.0001	0.0749 ††	-0.0479	0.37 ***	0.0001

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table 3.2. Linear regression for total dissolved P (TDP) loads in percolate with all methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the entire 90 minutes of rainfall from soils with Olsen P concentrations <200 mg kg⁻¹ (n=16 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	25.40 a†	-139.38	0.48 **	0.0029	0.708 b	4.07	0.32 *	0.0092	8.900	-43.63	0.15 *	0.0218
Olsen (OlsP)	3.76	31.07	0.15	0.0707	0.124	7.12	0.16	0.0786	0.817	40.78	0.02	0.0974
Modified Kelowna (MKP)	4.01	-37.92	0.34 *	0.0179	0.07	9.85	0.10	0.1843	1.320	-2.66	0.09	0.0746
Mehlich 3 (M3P)	2.35	-32.29	0.26 *	0.0433	0.08	5.99	0.20	0.0515	0.875	-8.34	0.08	0.0980
OlsP/(P150)	6.64	74.49	0.13	0.1722	0.93	7.32	0.17	0.0703	6.700	8.46	0.14 *	0.0242
M3P/(P150)	4.14	35.61	0.22	0.0669	0.557	6.44	0.21 *	0.0416	4.160	-13.63	0.24 **	0.0024
OlsP/M3(Ca+Mg)α ₁ ¶	2.48	115.4	0.05	0.4192	0.035	14.99	0.002	0.8350	1.940	47.65	0.04	0.2414
M3P/M3(Ca+Mg)α ₁	1.71 ‡	86.43	0.10	0.2426	0.042	14.49	0.01	0.7291	1.640	25.11	0.11	0.0540
OlsP/((2xP150)+OlsP)	10.56	22.82	0.23	0.0601	1.72	3.38	0.31 *	0.0106	10.640	-23.63	0.25 **	0.0018
M3P/((2xP150)+M3P)	9.82 a	-51.9	0.34 *	0.0186	1.07 b	2.53	0.32 **	0.0089	9.190	-70.23	0.34 ***	0.0002
OlsP/(M3(Ca+Mg)α ₂ + OlsP) #	6.93 ‡	29.7	0.16	0.1247	0.082	14.05	0.01	0.6720	3.98 ††	8.14	0.09	0.0759
M3P/(M3(Ca+Mg)α ₂ + M3P)	6.60 ‡	-29.81	0.22	0.0655	0.13	12.25	0.03	0.4615	4.30 ††	-34.23	0.15 *	0.0216
OlsP/(PSI+OlsP) §§	7.01 a§	-40.68	0.33 *	0.0262	0.77 b	3.88	0.27 *	0.0197	6.44 ††	-58.52	0.31 ***	0.0005
WEP/(PSI+WEP)	13.13 a§	-66.59	0.64 ***	0.0003	2.12 b	5.52	0.32 **	0.0091	12.54 ††	-49.83	0.64 ***	<0.0001
MKP/(PSI+MKP)	6.63 §	-48.81	0.31 *	0.0309	0.561	6.19	0.19	0.0532	5.90 ††	-59.91	0.29 ***	0.0008
M3P/(PSI+M3P)	6.12 a	-76.550	0.27 *	0.0479	0.575 b	1.850	0.29 *	0.0144	5.23 ††	-81.370	0.24 **	0.0027

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

found very strong relationships between leachate P and M3-P, in addition to WEP. Our results were also inconsistent with the observations of British researchers Hesketh and Brooks (2000) and Heckrath et al. (1995), who showed that a simple agronomic soil test, Ols-P, was related to P leaching through the soil profile. These researchers identified a change point at 60 mg kg^{-1} Ols-P where the amount of P leached increased drastically. Conversely, our data showed no such change point for any of the simple STP methods examined. However, the soils used by the British researchers had a very narrow range of properties for both studies. Wide differences in soil properties and P buffering capacity within our groups of soils may have obscured our ability to detect the potential for change point behavior within each group, let alone for a simple soil type.

Degree of phosphorus saturation (DPS) has also been used to determine the risk of P leaching. In the Manitoba soils, $\text{DPS}_{(\text{M3CaMg})}$ was poor at predicting percolate TDP concentrations, with r^2 values ranging from 0.01 to 0.10 for fine textured soils and 0.08 to 0.30 for coarse soils, 0.07 to 0.22 for all soils combined. Linear correlations for $\text{DPS}_{(\text{P150})}$ were slightly better with r^2 values between 0.19 and 0.45 for coarse soils, 0.42 to 0.70 for fine textured soils and 0.23 to 0.49 for all soils combined. All four methods of $\text{DPS}_{(\text{PSI+STP})}$ produced strong linear relationships with percolate for the fine textured group (Table 3.1). However, for the coarse group and all soils, only the WEP version of $\text{DPS}_{(\text{PSI+STP})}$ produced a highly significant relationship with TDP in percolate, with an $r^2=0.62$ in both cases; all other methods of determining soil P that we used had r^2 values of less than 0.4 (Table 3.1). Studies conducted by Maguire and Sims (2002a, b) and Hartz and Johnstone (2005) also observed very strong relationships between DPS in soil and TDP in percolate water. Hartz and Johnstone determined DPS as a single point

isotherm using CaCl_2 and KH_2PO_4 , similar to the Bache and Williams (1971) method used in our study.

The trends observed with TDP concentrations are mirrored by the TDP loads; the only method that shows promise for predicting percolate TDP is $\text{DPS}_{(\text{PSI}+\text{STP})}$ with WEP as the STP method (Table 3.2). This is especially true for the coarse soils and when all soils are grouped together with $r^2 = 0.64$ ($p < 0.001$) for both. The percolate load data is strongly influenced by some of the very coarse soils that had high STP which allowed 47-91 L of water to percolate through the soil boxes, compared to a mean of 9 L of percolate for the fine textured soils.

One of the reasons for the superior performance of WEP for predicting percolate TDP concentration and load may be due to displacement of prewetting water from the soil boxes. The soils were prewetted to field capacity prior to rainfall to ensure that runoff occurred. The prewet water was in contact with the soil for as much as 20 hours before being gravity drained. In many cases, the majority of water collected as percolate was probably prewet water that was held in the soil matrix. Approximately 20 and 25 L of the prewet water was held by each tray of soil at field capacity and a mean of 9 L and 18 L of percolate water was displaced from the fine and coarse textured soils respectively, during the 90 minute rainfall event. Therefore, the water collected was likely a result of displacement of water through the soil profile. The long exposure of the prewetting water to the soil matrix more closely resembled the soil test water extraction procedure, allowing more intimate contact between soil and percolating water than for runoff water.

3.4 Conclusion

The percolate data from the rainfall simulations conducted with Manitoba soils are not consistent with what is commonly found in the literature. Of the simple soil test P tests, only water extractable P (WEP) showed potential for use in predicting subsurface percolate total dissolved P (TDP) mobility to subsurface water within a textural group. As for the more sophisticated methods of P measurement the $DPS_{(PSI+STP)}$ method used by Casson et al. (2006) using WEP in a ratio with P saturation index was able to produce linear regressions that were strong and consistent across textural groups and accounted for at least 62% for TDP concentration and 64% for TDP load, when all soils were combined. These results are different from those in the literature where Olsen P and a variety of methods of determining DPS not only were able to predict TDP in percolate water but showed a distinct change point in STP or DPS where more P was released to percolate. The reason for WEP outperforming other methods may be that the amount of water that percolated through our soils may have been less than in other studies. Also, a large proportion of percolate collected during our study was probably displaced from the prewetting water and was in contact with the soil matrix for a long period (up to 20 hours), resulting in conditions that closely resembled the soil test extraction procedure for WEP.

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4.0 Summary and Contributions to Knowledge

Rainfall simulation studies with packed soil boxes are one small step toward moving away from the bench top and applying the principles of nutrient loss developed in the lab to actual field conditions and situations. This study has identified soil test phosphorus (STP) and degree of P saturation (DPS) methods that show promise in the ability to predict the load and concentration of P that can be potentially lost from runoff and to a lesser extent leaching.

Water extractable P (WEP), an environmental P extraction method, did not predict runoff P as accurately as expected, even though it closely resembles rain water. However, although the chemical nature of the extractant is the same as rain, the transport processes that occur within the rainfall runoff system are much different from those in a laboratory extraction procedure. Rain water continuously washes over only the top few millimeters of the soil surface and this is different from a 10:1 (water: soil) laboratory batch extraction that mixes all the soil and all the water during a one hour shaking period. However, compared to runoff water, the percolate water has more contact with soil and this process may better resemble the WEP soil test method. As a result, WEP appears to predict the risk of P leaching better than P runoff, at least within a soil textural group.

For Manitoba soils, Olsen P (Ols-P) was able to predict runoff P very well within textural groups and across soil textures. This may be because the process of runoff water continuously removing labile reserves of P from a small proportion of the soil may be analogous to root uptake of labile P, especially in fine textured soils where the effective depth of interaction (EDI) is very shallow (Sharpley, 1985). As a result the runoff water is able to extract some of the more strongly held P because a small depth of surface soil is

always being washed with a large volume of fresh water. By gathering percolate water, we were able to test the hypothesis that the shallow effective depth of interaction (EDI) of the rainwater with the soil led to Ols-P being the best STP method for predicting runoff P losses. Indeed, when the percolate data was analyzed, it was apparent that the Ols-P method was the weakest method for predicting P losses through percolate water, even though it had been the strongest for predicting runoff losses.

Mehlich 3 and Modified Kelowna showed promise for predicting runoff P losses with stronger relationships for the coarse textured soils than the Ols-P method. However, these methods were not as consistent as Ols-P across textural groups or when all the soils were combined. These two simple STP methods were also poor at predicting P losses in the percolate water. Mehlich 3 had the strongest relationship with TDP in percolate water with an $r^2 = 0.48$ which is still too low for accurate prediction of percolate loss. The reasons for the relatively poor performance of the acidic extracts, relative to Olsen P are not known. However, the Olsen test is well documented as an excellent agronomic test for measuring labile P alkaline soils (Beegle, 2005).

Several methods of estimating the degree of P saturation (DPS) had strong relationships with runoff and percolate TDP losses. The methods that were particularly strong were those that had STP added to the phosphorus sorption capacity; these were especially suited for predicting runoff TDP losses in coarse soils. However, some of these methods had weak predictive ability in the fine soils and when all soils were combined they were no longer able to accurately predict runoff TDP losses. Conversely, for percolate losses WEP/ (PSI+WEP) was a strong predictor of TDP losses for each textural group and for all soils combined.

Our study was able to show that simple agronomic soil tests such as Ols-P may allow the use of a single extraction coefficient to predict runoff P losses across many soils with different P concentrations and a wide range of soil textures, ranging from 2 – 83 % clay for neutral to alkaline soils. However, as stated earlier these findings are based on simulated rainfall over packed soil boxes and scale becomes a question. Moving to natural runoff from entire fields or watersheds creates many more variables that need to be accounted for. For example, Alberta researchers found that concentrations of P in natural runoff from watersheds were up to 6 times greater than from a rainfall simulator (Wright et al., 2006).

Another limitation of using simulated rainfall data for quantifying the P that comes off of fields is the slope that was used in this study (5%) is rarely seen in Manitoba. As a result, the amount of land at risk of water erosion in Manitoba is only 1% of the total land in annual crop production (van Vliet et al., 2005). The shallow slope of Manitoba's natural landscape allows more time for water to infiltrate. However, if the soil fully saturated there may be opportunity for the water to slowly solubilize labile P in a manner that does not resemble fast flowing runoff water moving down a steep slope. For example, if this water moves through at a slow but steady rate this may result in a high proportion of dissolved P (DP) fraction of the total P lost, a fraction that is highly available to algae, increasing the potential for eutrophication.

Another difference between our rainfall simulation and field conditions was the rainfall intensity of 75 mm hr^{-1} for a 90 minute duration that rarely, if ever, occurs in Manitoba. Again, we needed to ensure that runoff occurred and this is the rainfall rate that the USDA's national research project for simulated rainfall uses in their protocol

(National Phosphorus Research Project, 2005). We attempted to use a rate of 35 mm hr^{-1} to duplicate more typical field conditions and to increase the depth of interaction, but runoff could not be reliably generated. However, a rainfall event of 75 mm hr^{-1} for a duration of 10 minutes is a 1 in 2 year probability. Therefore, maintaining the rainfall intensity over a shorter duration may be a better way to simulate Manitoba rainfall runoff conditions.

Once the relationship between P in soil and P in runoff is clearly defined for soils in Manitoba, we need to develop methods to reduce the amount of dissolved P losses under snowmelt dominated runoff. Most of the beneficial management practices (BMPs) that have been developed for reducing P losses are for particulate P losses in rainfall driven runoff. These may not work for reducing dissolved P losses but in some cases may actually add to the losses of dissolved P (Bechmann et al., 2005; Sheppard et al., 2006). More work is needed to develop BMPs that will increase the infiltration rate of soil to allow for more water to flow downward rather than off the surface. However, most of the runoff in Manitoba occurs on frozen or partially frozen soils during spring snowmelt (Glozier et al., 2006; Sheppard et al., 2006) where infiltration is severely limited by ice in the soil. Perhaps this runoff water should be directed to holding ponds or wetlands as quickly as possible to reduce exposure to soil and then this water should be used for irrigation.

In summary, our simulated rainfall study showed that Ols-P is an accurate predictor of runoff TDP losses across textural groups but fails to accurately predict percolate TDP losses. For the percolate TDP losses the only simple STP method that could predict P losses was WEP and only within textural groups. When using WEP/

(PSI+WEP) to estimate DPS we could predict TDP losses in percolate from each textural group and from all soils, combined. Although this knowledge represents an important step forward in our understanding of relationships between runoff losses of P and measurements of soil P, additional work is needed to characterize these relationships under field conditions. Lastly, the most important step is to design BMPs for reducing runoff P losses under Manitoba conditions. In order to be effective these BMPs should be developed and validated for Manitoba's soils, landscapes, and climate.

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Appendix I: STP and DPS regressions with TDP for 0- 30 minute interval

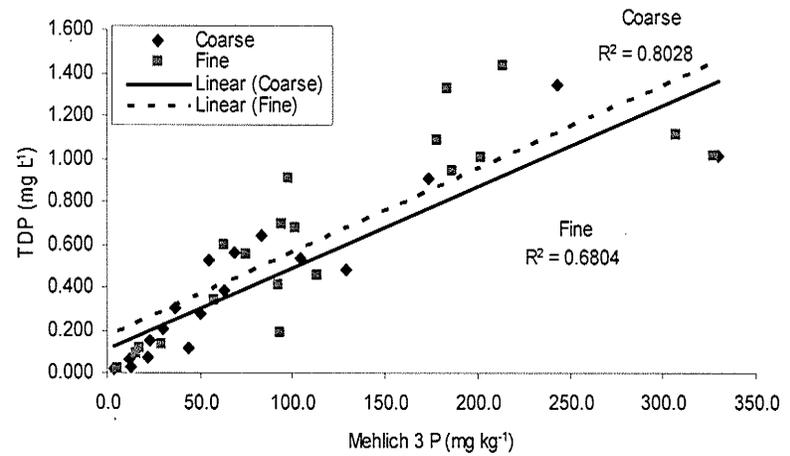
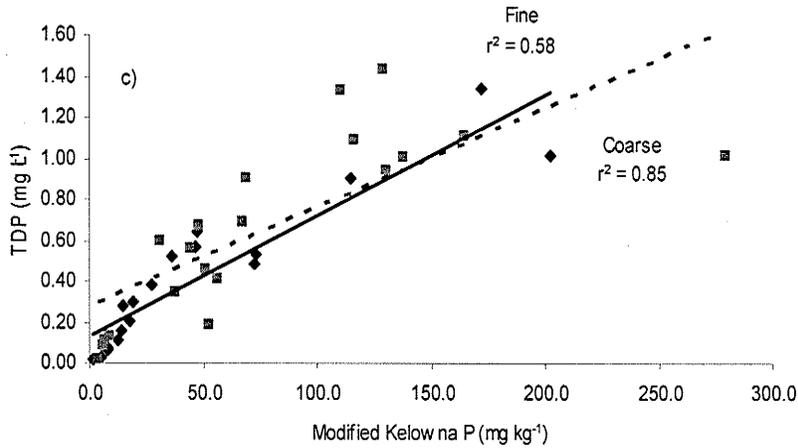
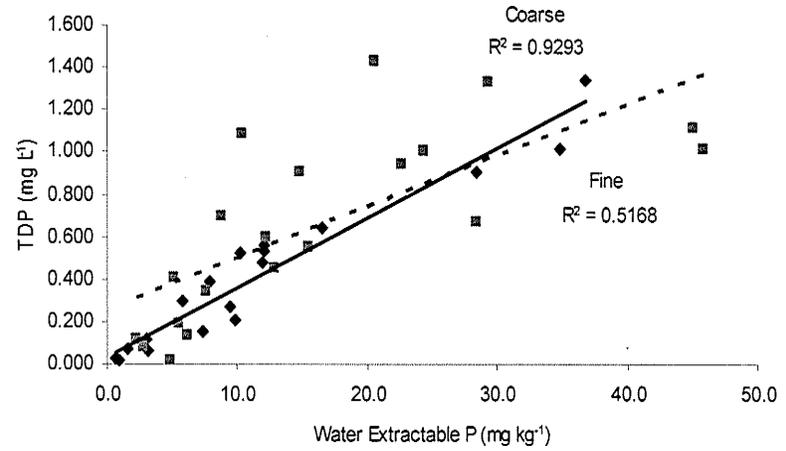
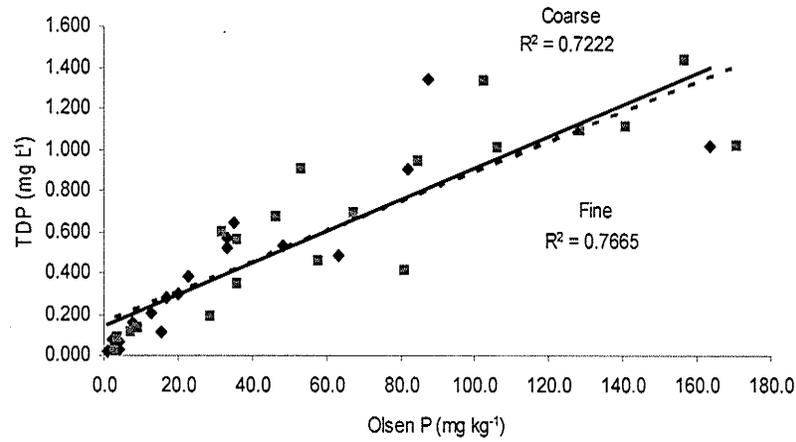


Fig I.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in the first 30 minutes of runoff.

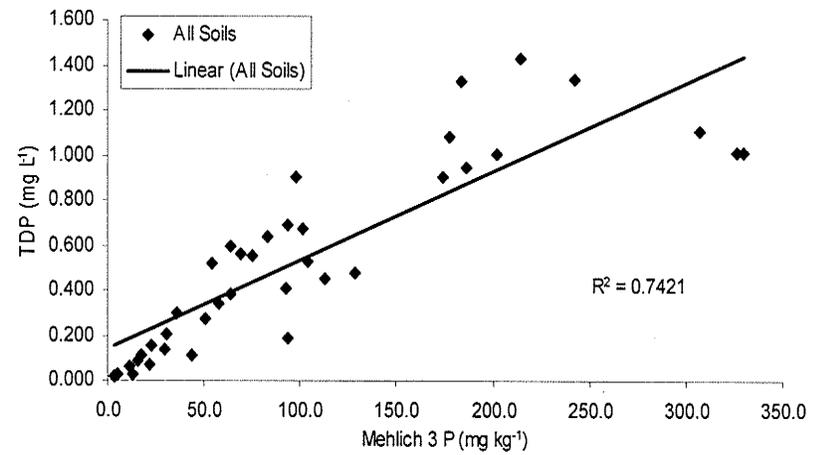
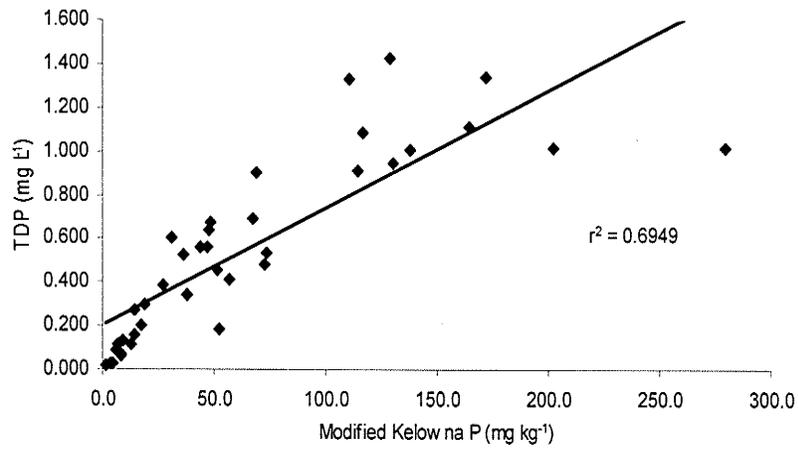
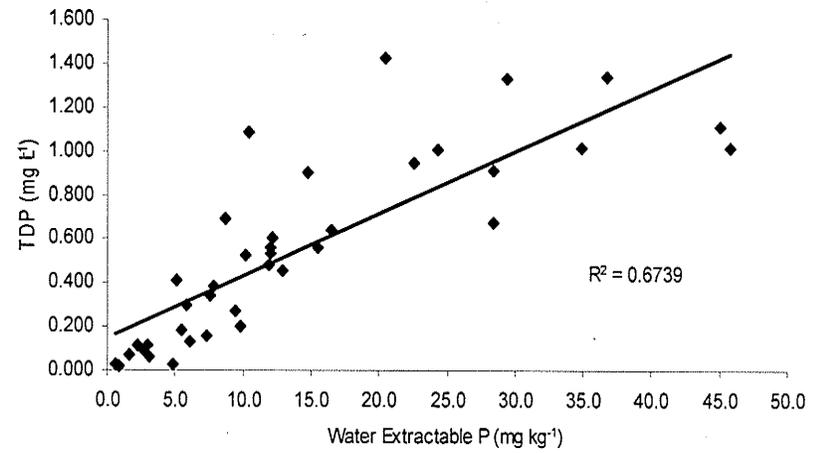
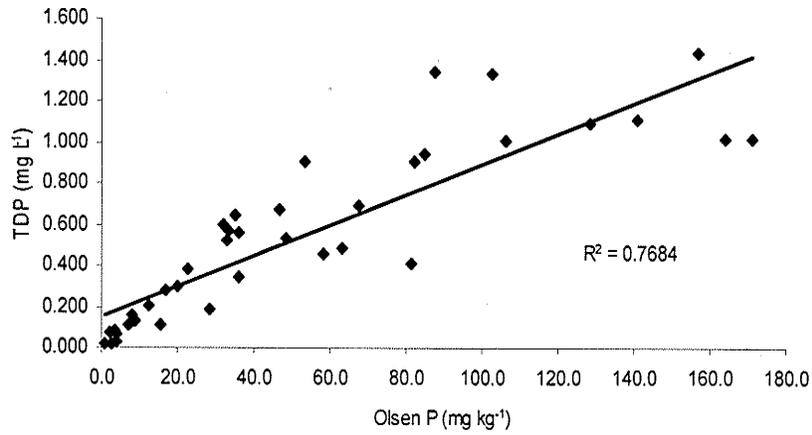


Fig I.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in the first 30 minutes of runoff.

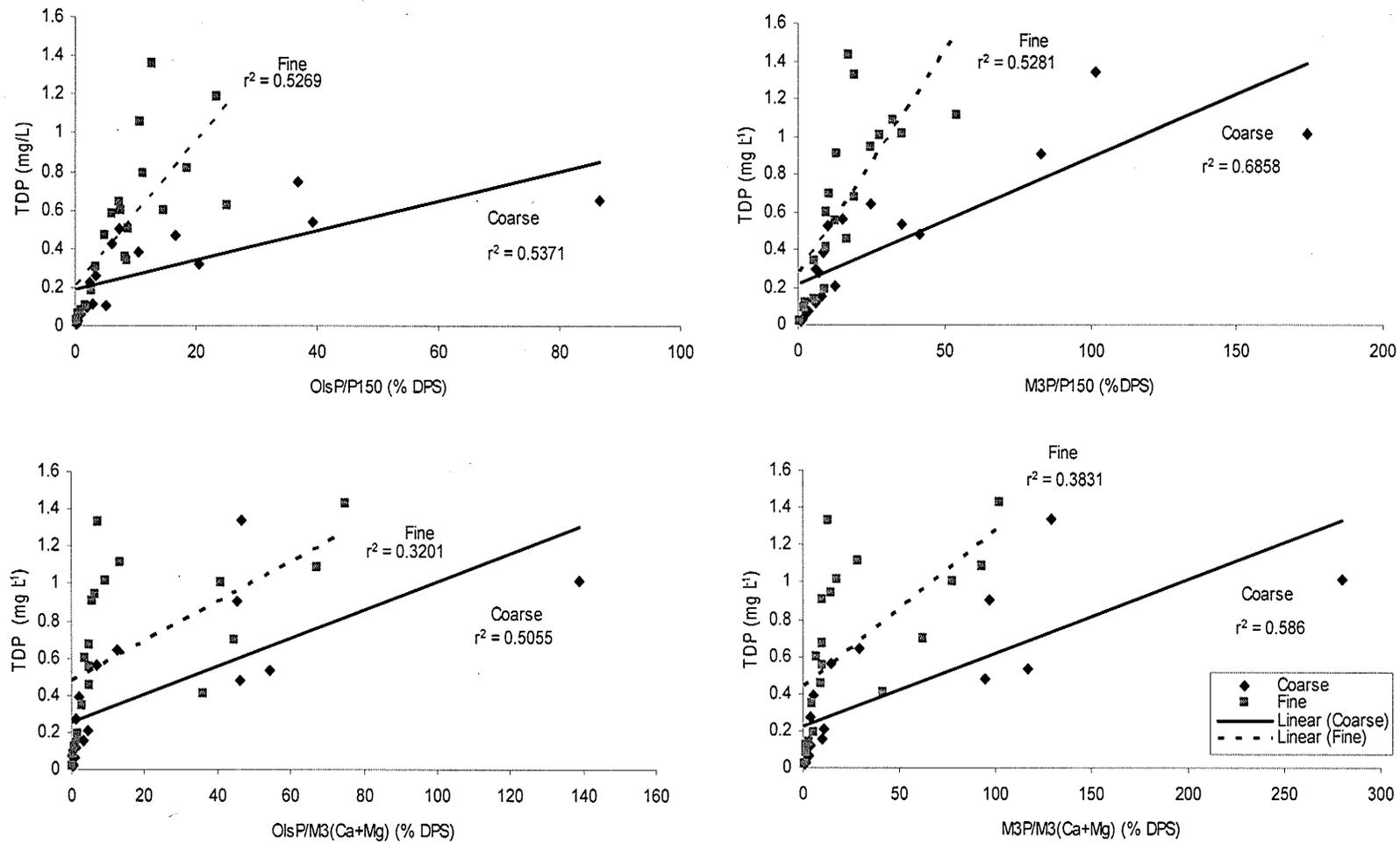


Fig I.3: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) in the first 30 minutes of runoff.

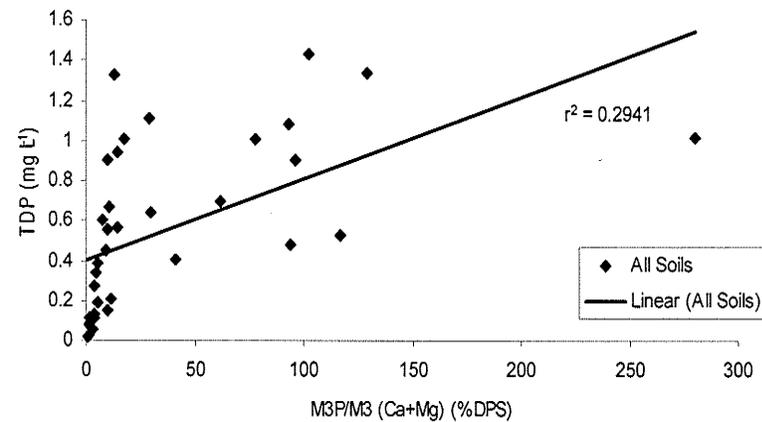
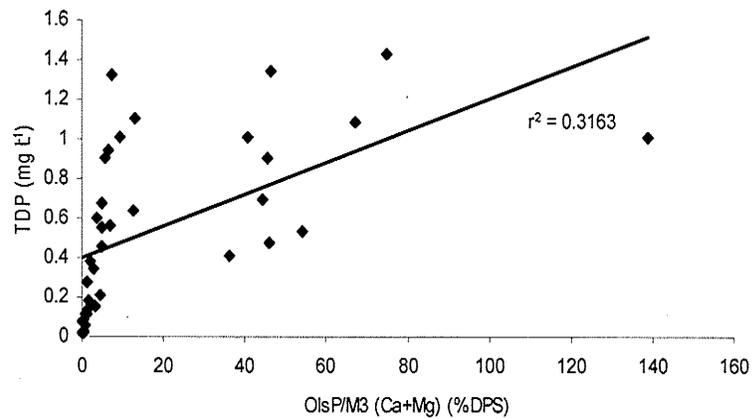
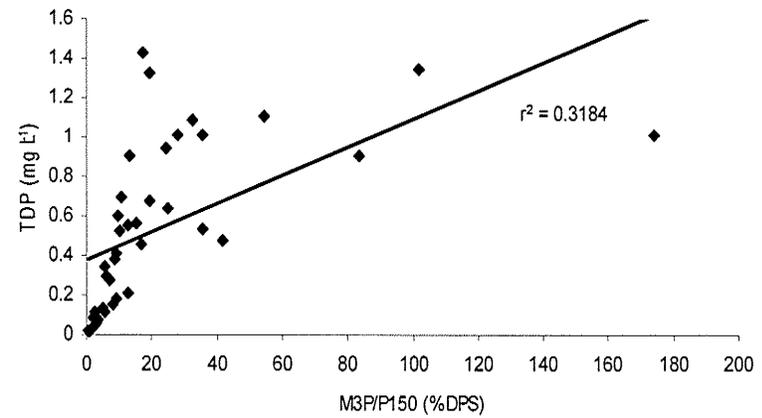
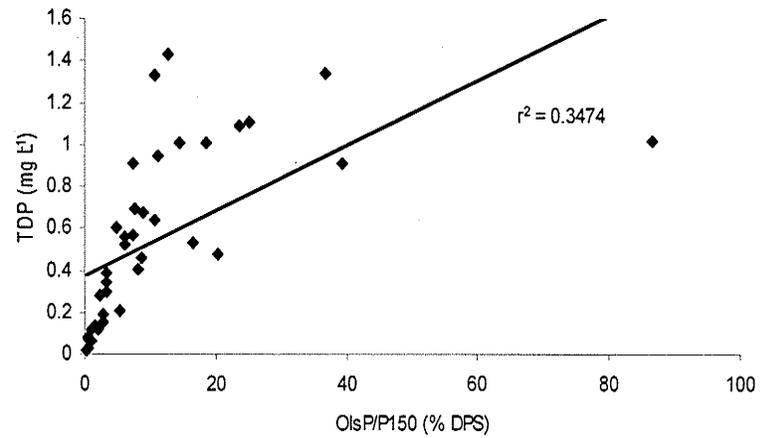


Fig I.4: Linear regression for all soils with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) in the first 30 minutes of runoff.

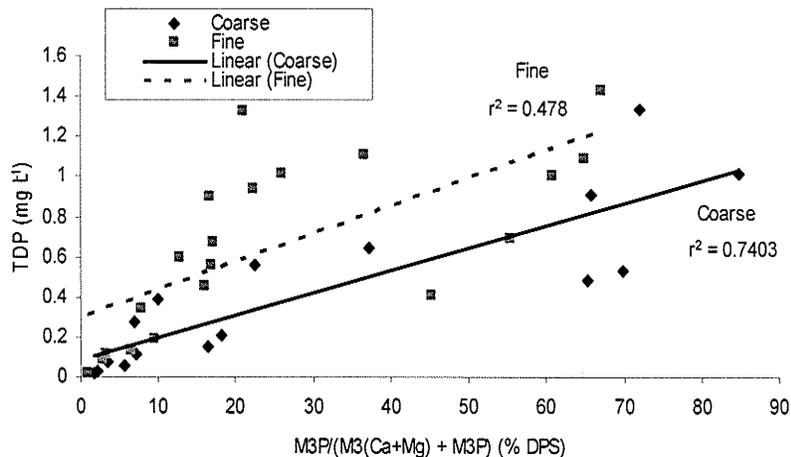
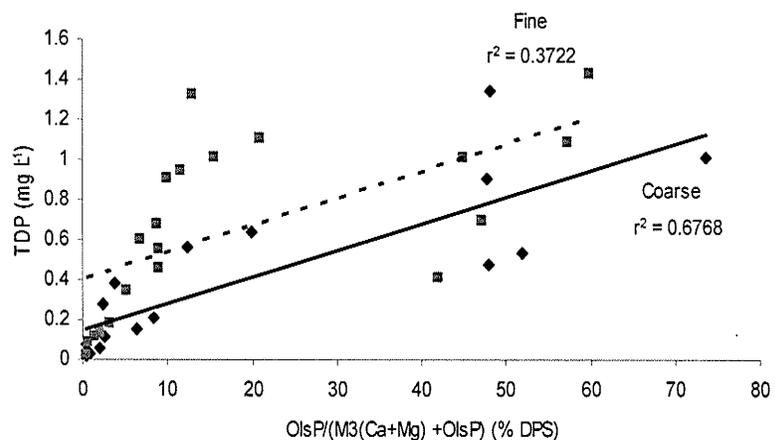
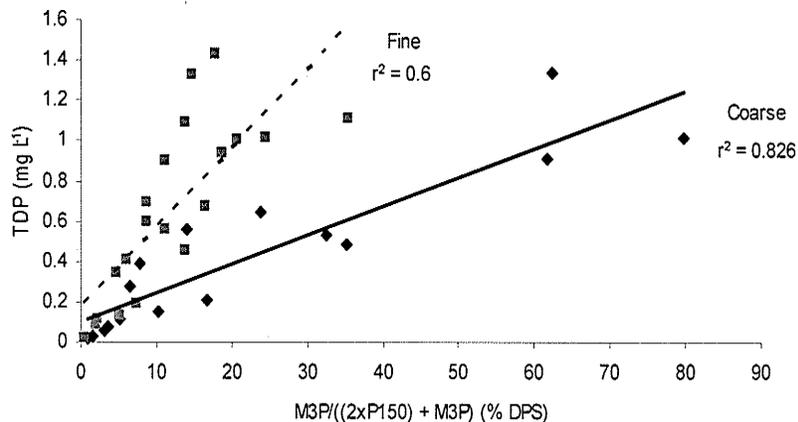
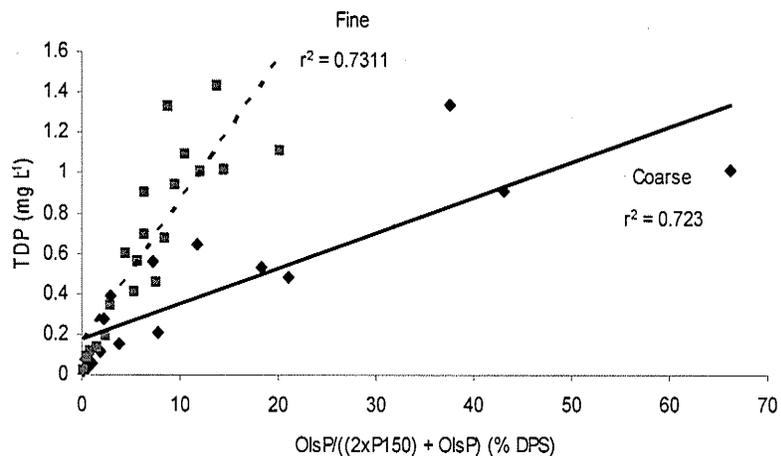


Fig I.5: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

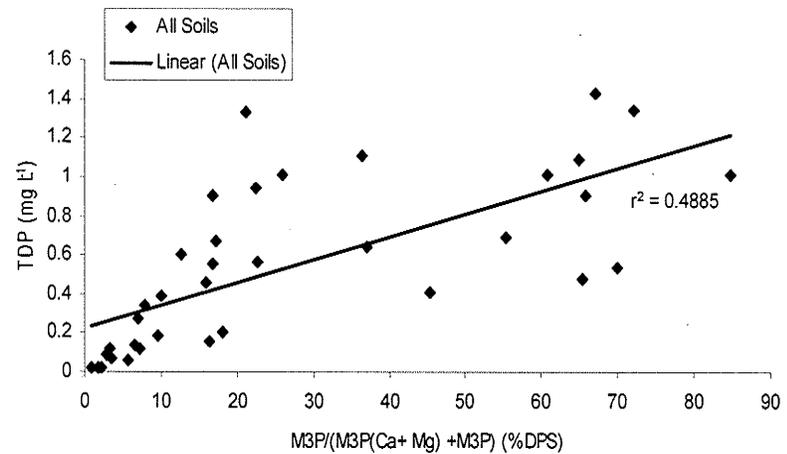
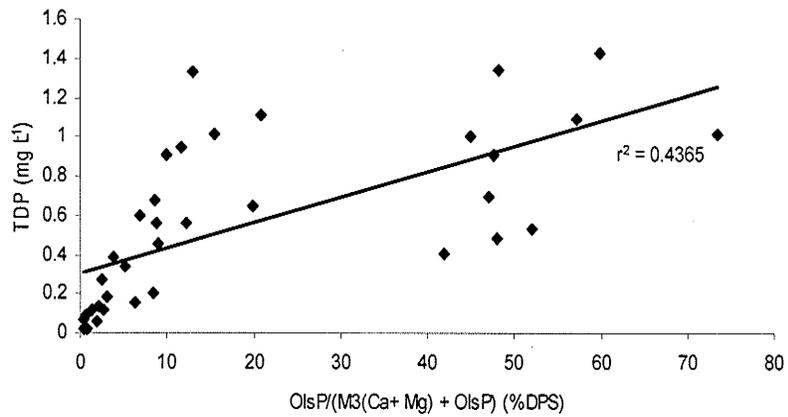
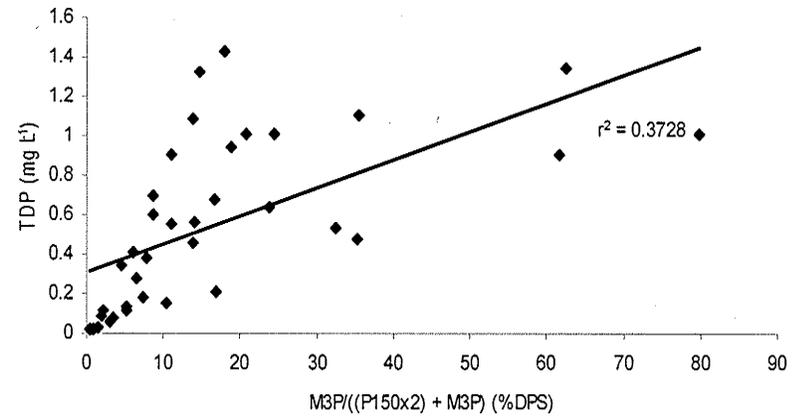
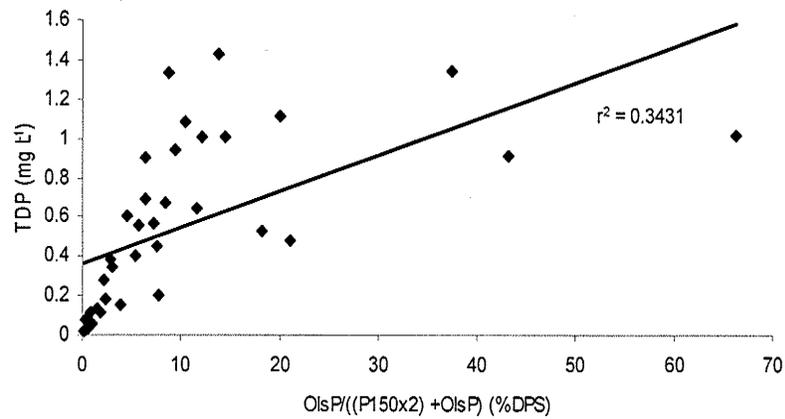


Fig I.6: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

Table I.1: Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-30 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0327 a	0.0371	0.93 ***	<0.0001	0.0240 a	0.2642	0.52 ***	0.0004	0.0283	0.1453	0.67 ***	<0.0001	0.0273	0.1532	0.769 ***	<0.0001
Olsen (Ols-P)	0.0076 a†	0.1450	0.72 ***	<0.0001	0.0073 a	0.1632	0.77 ***	<0.0001	0.0074	0.1539	0.77 ***	<0.0001	0.0075	0.1442	0.815 ***	<0.0001
Modified Kelowna (MK-P)	0.0059 a	0.1308	0.85 ***	<0.0001	0.0048 a	0.2787	0.58 ***	0.0001	0.0054	0.1971	0.70 ***	<0.0001	0.0065	0.1425	0.777 ***	<0.0001
Mehlich 3 (M3-P)	0.0038 a	0.1089	0.80 ***	<0.0001	0.0039 a	0.1758	0.68 ***	<0.0001	0.0040	0.1349	0.74 ***	<0.0001	0.0048	0.0755	0.728 ***	<0.0001
Ols-P/(P150)	0.0133 a	0.2413	0.60 ***	0.0001	0.0480 b	0.2291	0.64 ***	<0.0001	0.0156	0.3713	0.35 ***	<0.0001	0.0211	0.3721	0.338 ***	<0.0001
M3-P/(P150)	0.0067 a	0.2187	0.69 ***	<0.0001	0.0235 b	0.2684	0.53 ***	0.0003	0.0071	0.3817	0.32 ***	0.0002	0.0083	0.4306	0.215 **	0.0026
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0133 a§	0.2513	0.51 **	0.0020	0.0106 a	0.4784	0.32 **	0.0093	0.0081 ¶	0.3961	0.32 ***	0.0004	0.0119	0.3811	0.482 ***	<0.0001
M3-P/M3(Ca+Mg)α ₁	0.0039 a§	0.2272	0.59 ***	0.0005	0.0084 a	0.4387	0.38 **	0.0036	0.0041 ¶	0.4030	0.29 ***	0.0006	0.0058	0.4201	0.333 ***	0.0002
Ols-P/((2xP150)+Ols-P)	0.0170 a	0.1997	0.70 ***	<0.0001	0.0702 b	0.1551	0.73 ***	<0.0001	0.0184	0.3612	0.35 ***	0.0001	0.0262	0.3427	0.383 ***	<0.0001
M3-P/((2xP150)+M3-P)	0.0138 a	0.1308	0.79 ***	<0.0001	0.0390 b	0.1792	0.60 ***	<0.0001	0.0142	0.3104	0.38 ***	<0.0001	0.0186	0.4091	0.323 ***	0.0002
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0132 a§	0.1516	0.68 ***	<0.0001	0.0133 a	0.4091	0.37 **	0.0043	0.0130 ¶	0.3006	0.44 ***	<0.0001	0.0180	0.2069	0.484 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0112 a§	0.0810	0.74 ***	<0.0001	0.0138 a	0.3031	0.48 ***	0.0007	0.0116 ¶	0.2285	0.49 ***	<0.0001	0.0154	0.1910	0.458 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0100 a‡‡	0.1658	0.73 ***	<0.0001	0.0344 b	0.1311	0.75 ***	<0.0001	0.0118 §§	0.3146	0.40 ***	<0.0001	0.0149	0.3268	0.320 ***	0.0002
WEP/(PSI+WEP) ††	0.0138 a‡‡	0.2068	0.77 ***	<0.0001	0.0610 b	0.3647	0.37 **	0.0042	0.0123 §§	0.4262	0.23 **	0.0026	0.0188	0.3977	0.439 ***	<0.0001
MK-P/(PSI+MK-P) ††	0.0097 a‡‡	0.1510	0.73 ***	<0.0001	0.0275 b	0.1945	0.65 ***	<0.0001	0.0111 §§	0.3067	0.39 ***	<0.0001	0.0155	0.2541	0.492 ***	<0.0001
M3-P/(PSI+M3-P) ††	0.0097 a‡‡	0.0895	0.72 ***	<0.0001	0.0233 b	0.0982	0.67 ***	<0.0001	0.0114 §§	0.2226	0.44 ***	<0.0001	0.0155	0.1545	0.488 ***	<0.0001

*, **, *** significance at p < 0.05, p < 0.01, p < 0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p < 0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Appendix II: STP and DPS regressions with PP for 0- 30 minute interval

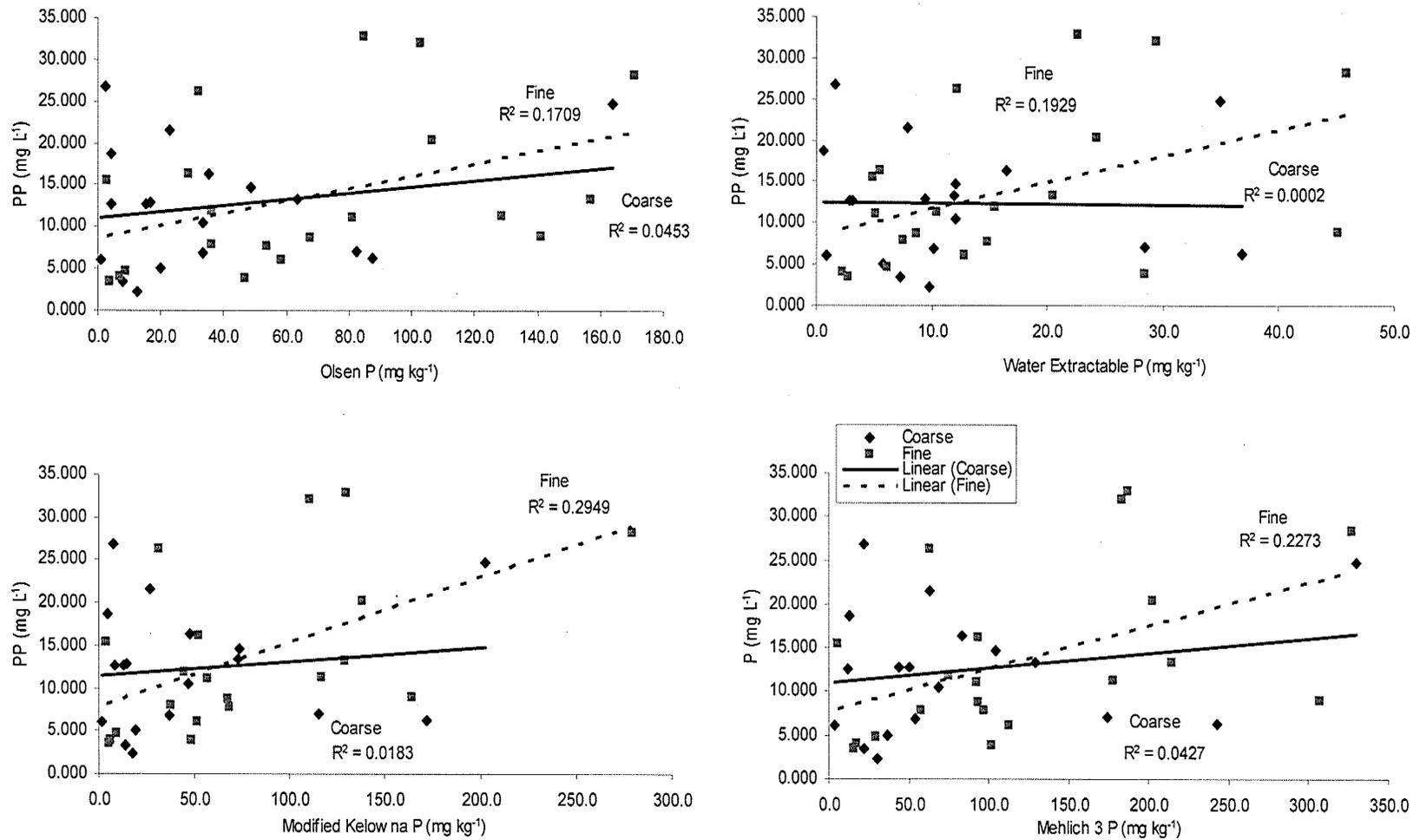


Fig II.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in the first 30 minutes of runoff.

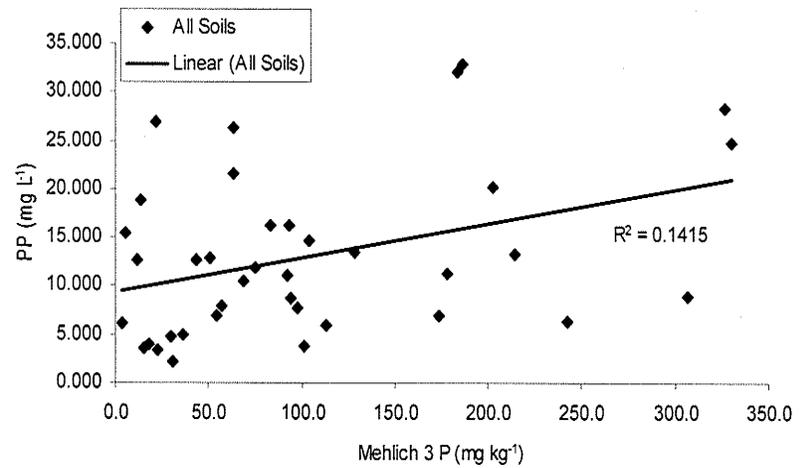
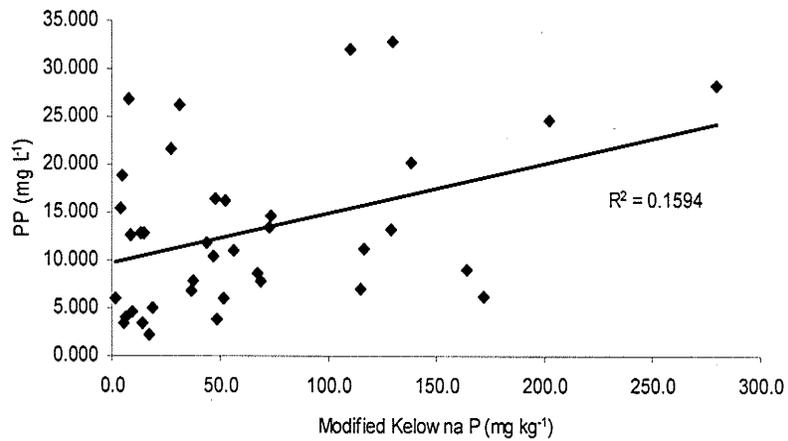
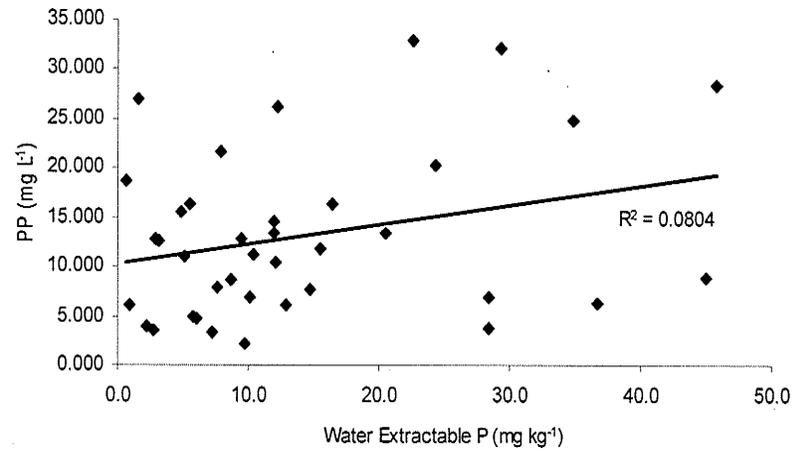
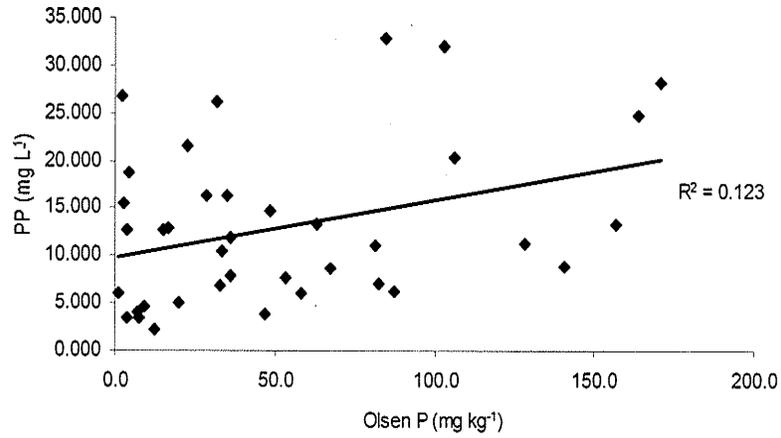


Fig II.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in the first 30 minutes of runoff.

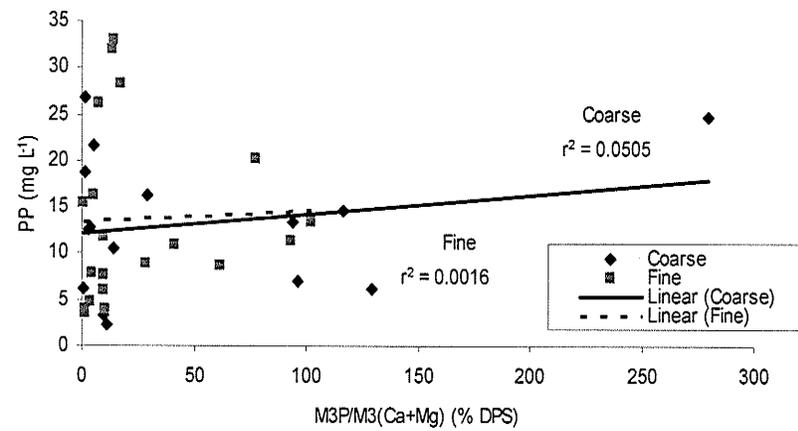
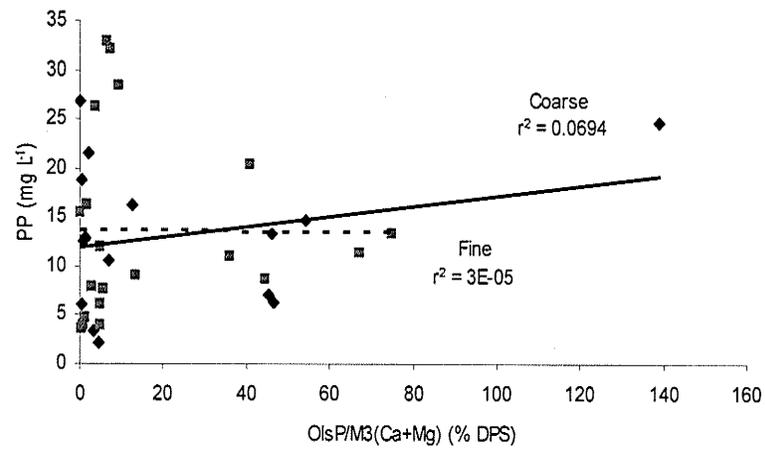
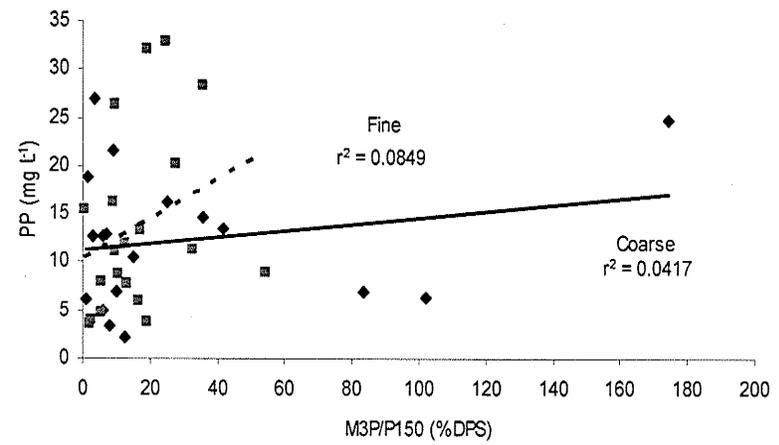
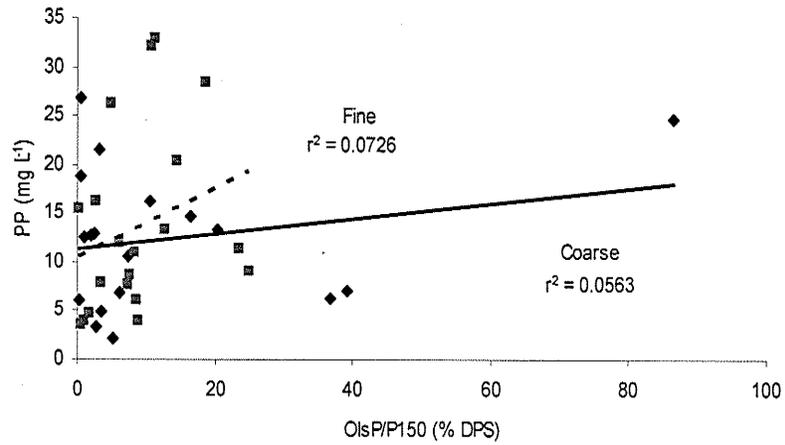


Fig II.3: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a). in the first 30 minutes of runoff

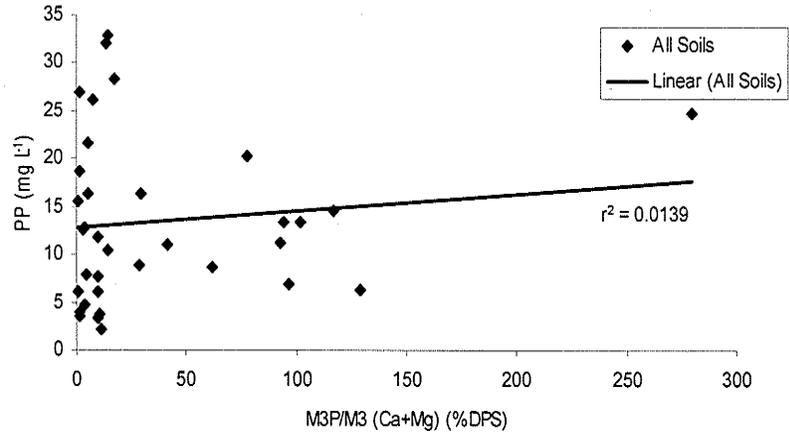
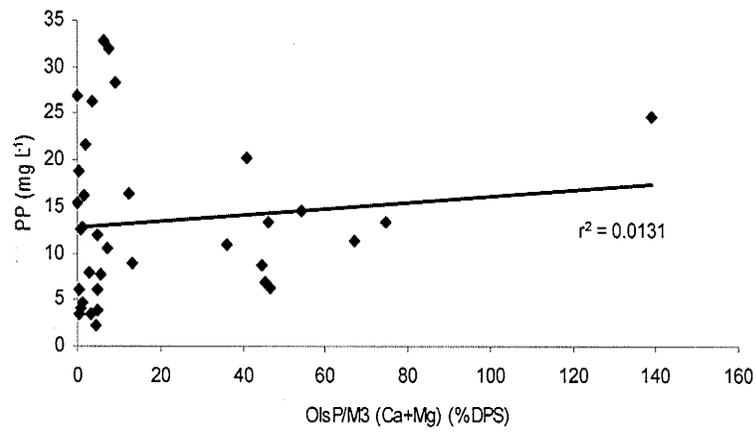
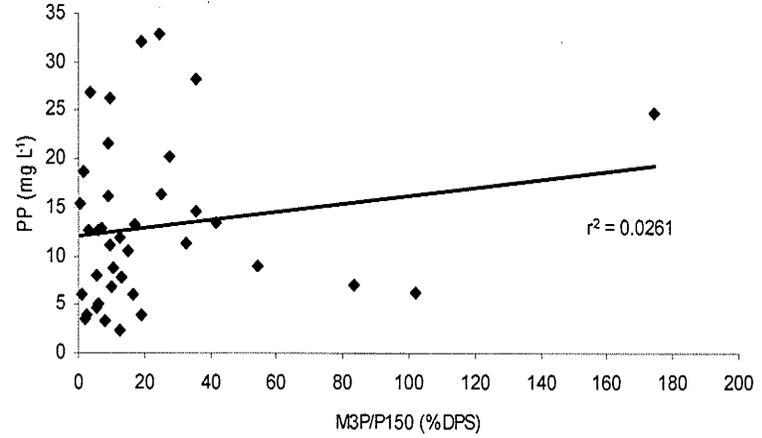
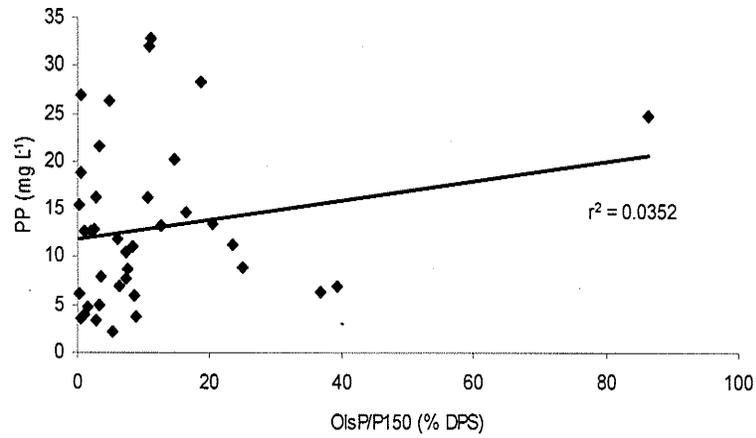


Fig: II.4: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a). in the first 30 minutes of runoff

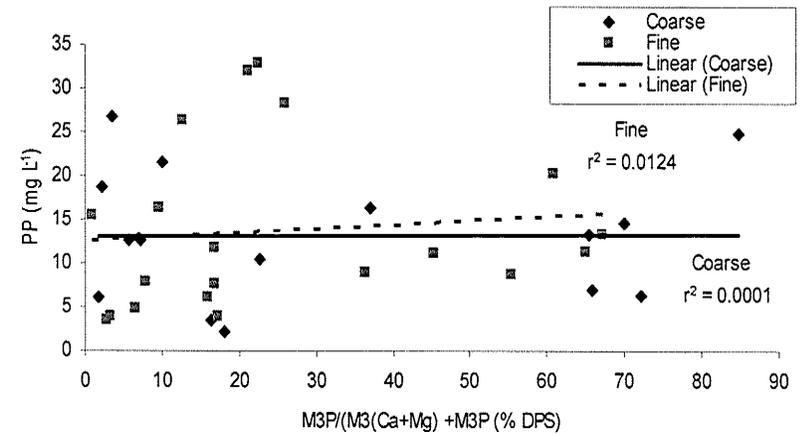
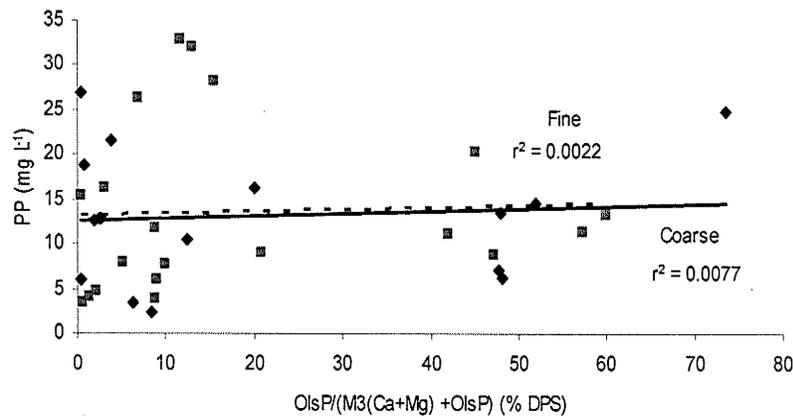
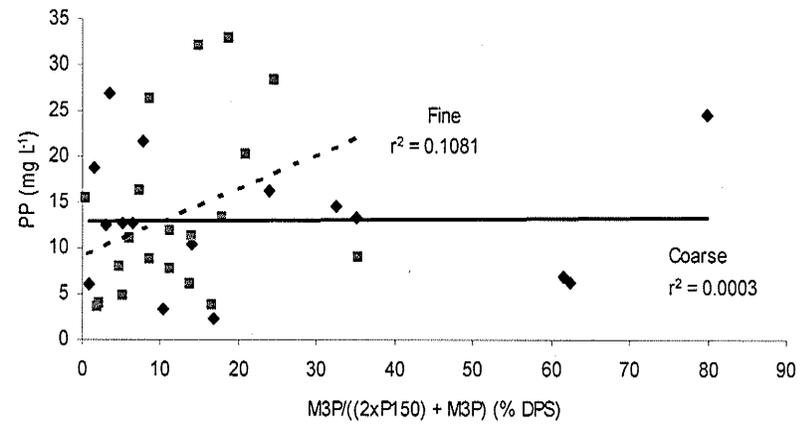
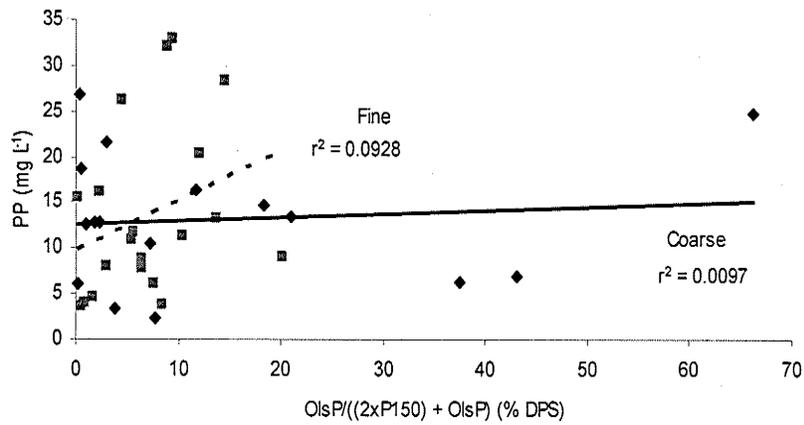


Fig II.5: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

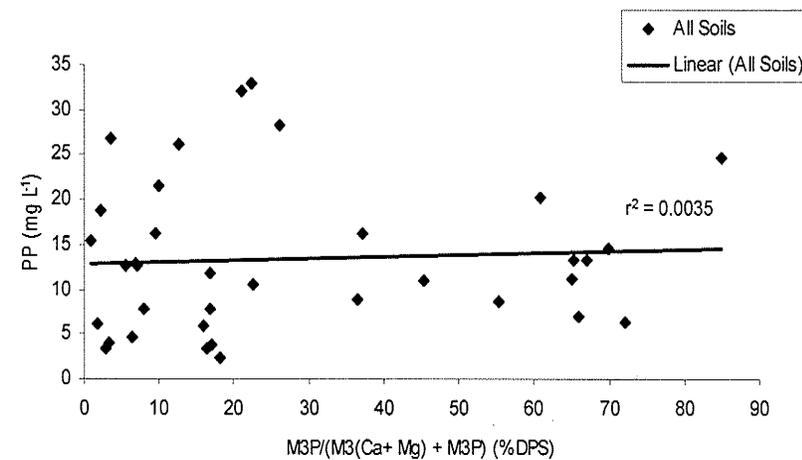
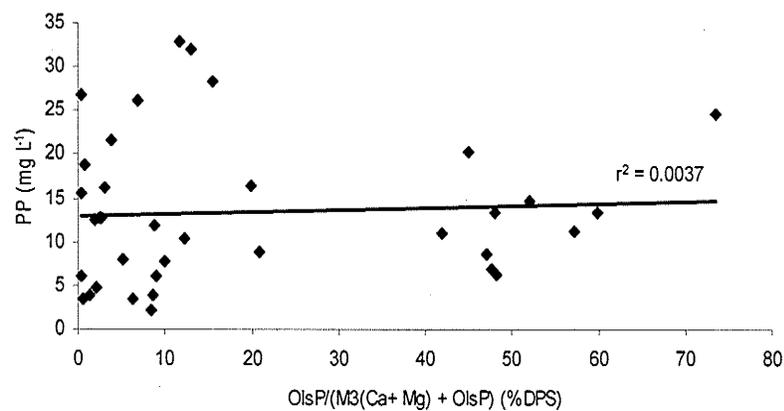
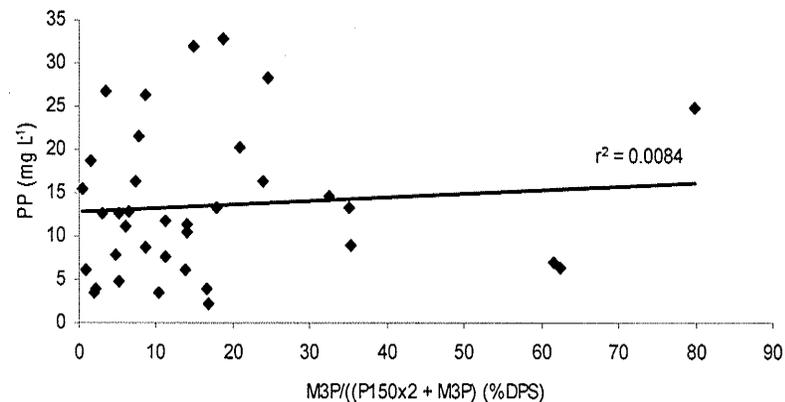
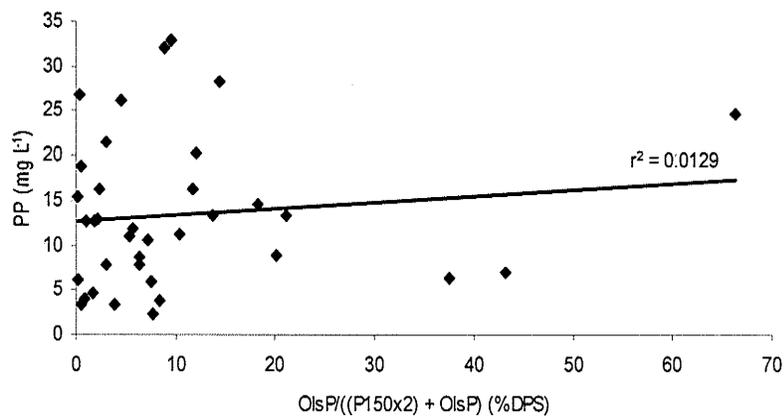


Fig II.6: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

Table II.1: Linear regression for concentration of particulate P (PP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-30 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	-0.0082	12.398	0.000	0.9611	0.32	8.500	0.193	0.0527	0.196	10.261	0.080	0.0846	0.156	10.720	0.117 *	0.0307
Olsen (OlsP)	0.0372	10.952	0.045	0.3965	0.0747	8.640	0.171	0.0700	0.0596	9.891	0.123 *	0.0309	0.048	10.356	0.153 *	0.0124
Modified Kelowna (MKP)	0.017	11.470	0.018	0.5922	0.0754	7.847	0.295 *	0.0134	0.052	9.688	0.159 *	0.013	0.048	9.826	0.200 **	0.0038
Mehlich 3 (M3P)	0.0171	10.895	0.043	0.4104	0.0491	7.667	0.227 *	0.0336	0.0347	9.436	0.142 *	0.0199	0.034	9.462	0.175 *	0.0072
OlsP/(P150)	0.0789	11.230	0.056	0.3431	0.3538	10.561	0.073	0.2507	0.0997	11.928	0.035	0.2595	0.125	11.914	0.055	0.1443
M3P/(P150)	0.0322	11.328	0.041	0.4162	0.206	10.323	0.085	0.2126	0.0408	12.100	0.026	0.3327	0.046	12.320	0.032	0.2716
OlsP/M3(Ca+Mg) α_1 †	0.0502 †	12.077	0.065	0.3585	0.0009	13.587	0.000	0.9932	0.0331 ¶	12.788	0.013	0.513	0.059	12.485	0.057	0.1625
M3P/M3(Ca+Mg) α_1	0.0205 †	12.202	0.046	0.4405	0.0146	13.205	0.002	0.8423	0.0179 ¶	12.775	0.014	0.5001	0.029	12.67	0.04	0.2444
OlsP/((2xP150)+OlsP)	0.0581	11.543	0.022	0.5596	0.546	9.817	0.093	0.1916	0.0824	12.217	0.0171	0.4336	0.125	12.071	0.040	0.2131
M3P/((2xP150)+M3P)	0.0251	11.773	0.007	0.7427	0.361	9.300	0.108	0.157	0.0532	12.163	0.013	0.4958	0.065	12.744	0.020	0.408
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0238 †	12.775	0.006	0.7767	0.022	13.286	0.002	0.8447	0.0224 ¶	13.077	0.003	0.742	0.057	12.709	0.023	0.3697
M3P/(M3(Ca+Mg) α_2 + M3P)	0.0010 †	13.245	0.000	0.9878	0.048	12.464	0.012	0.6408	0.0187 ¶	12.993	0.003	0.7457	0.043	12.647	0.017	0.4361
*	significant at p < 0.05															
**	significant at p < 0.005															
***	significant at p < 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix III: STP and DPS regressions with TP for 0- 30 minute interval

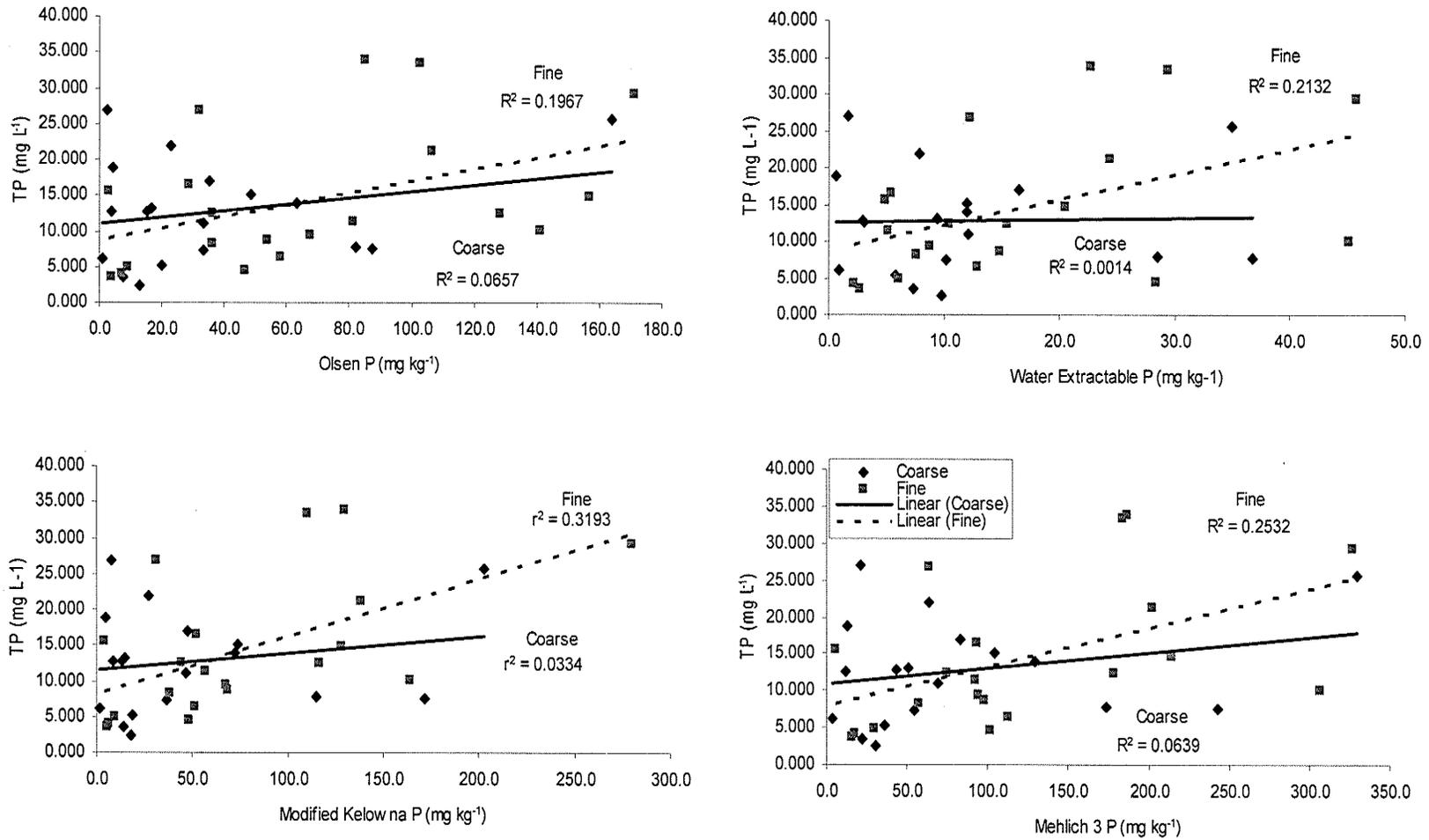


Fig III.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in the first 30 minutes of runoff.

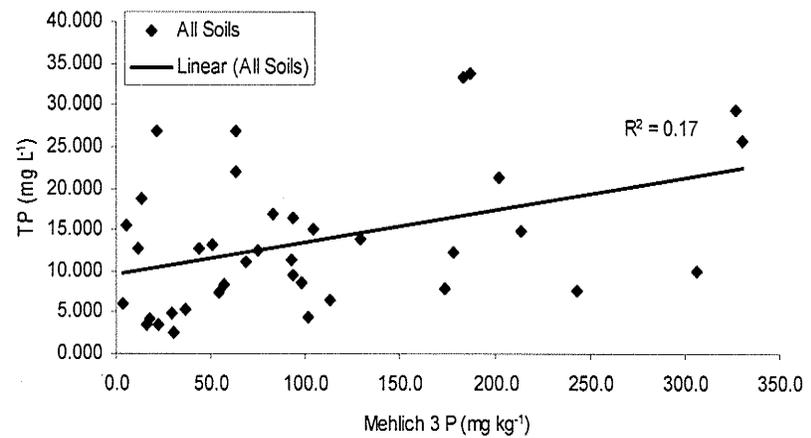
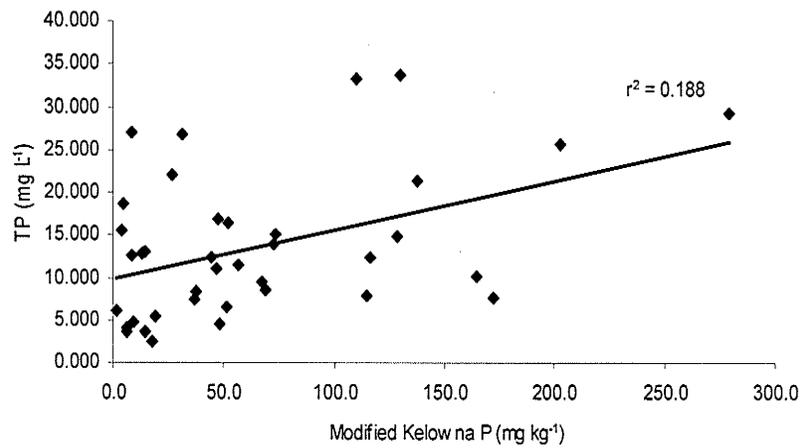
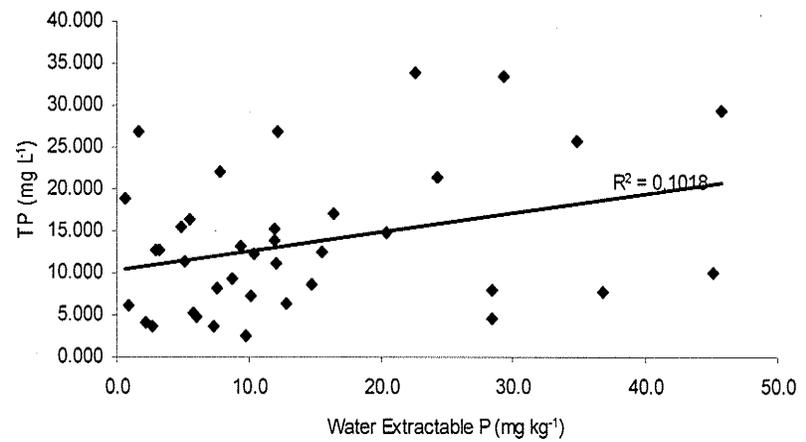
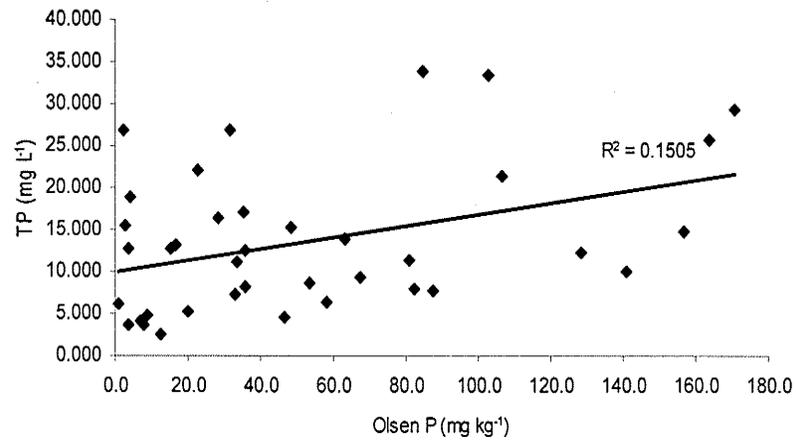


Fig III.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in the first 30 minutes of runoff.

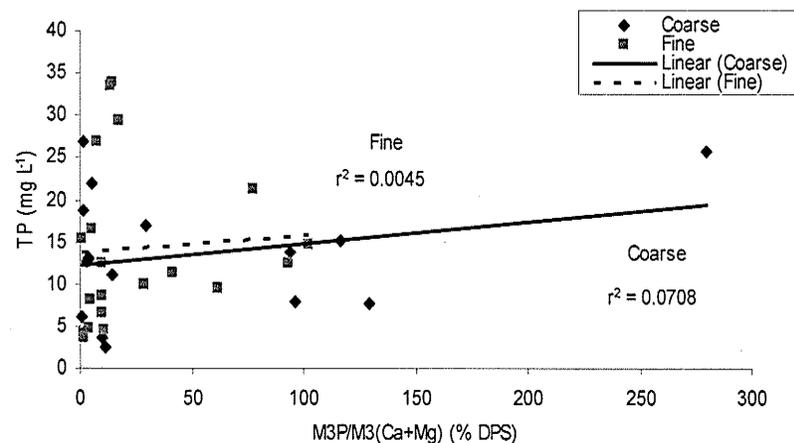
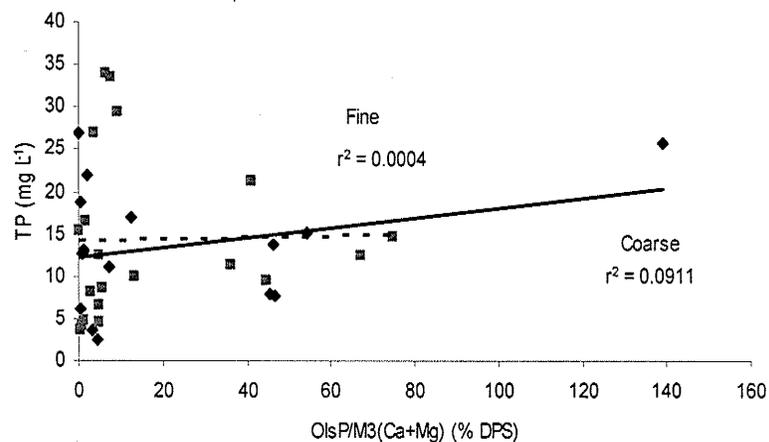
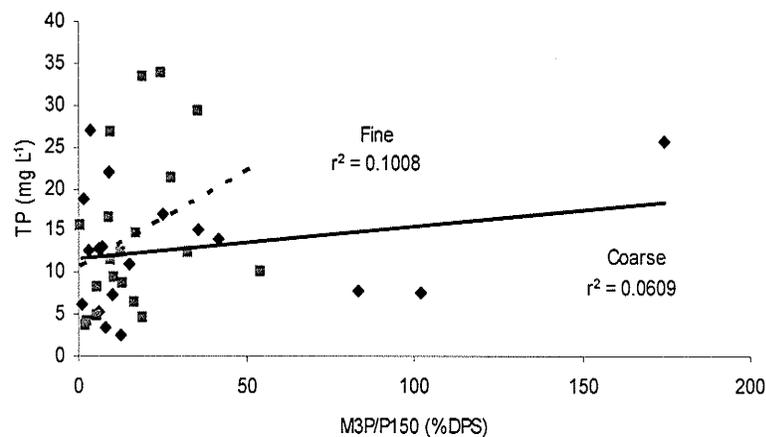
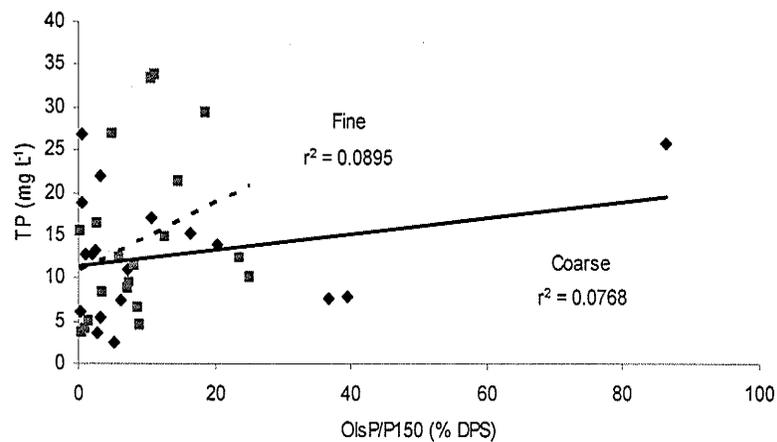


Fig III.3: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) in the first 30 minutes of runoff.

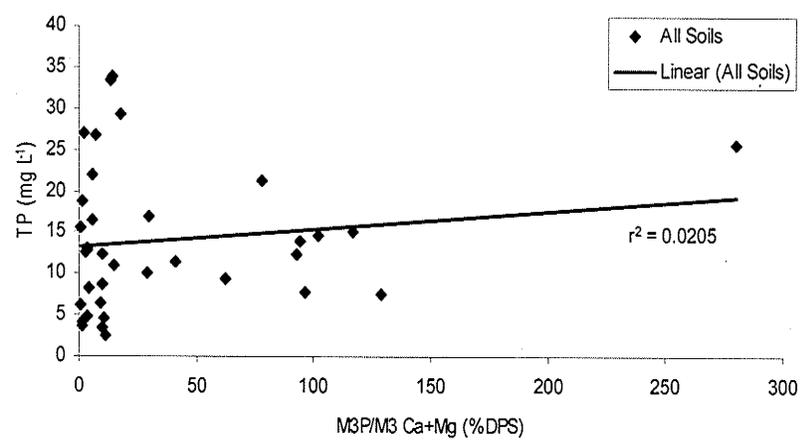
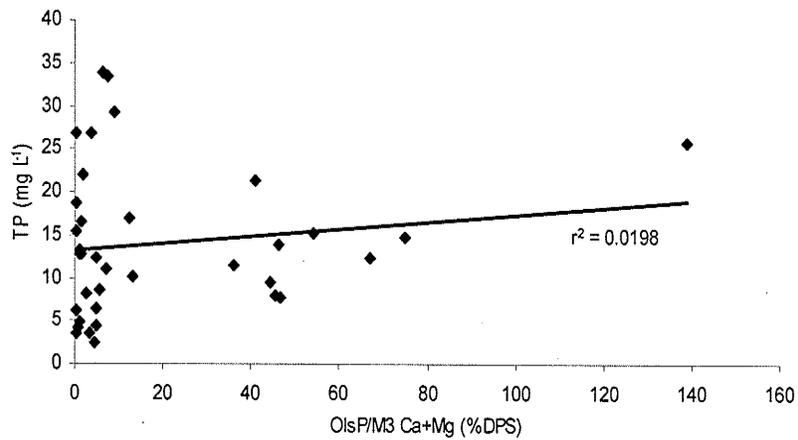
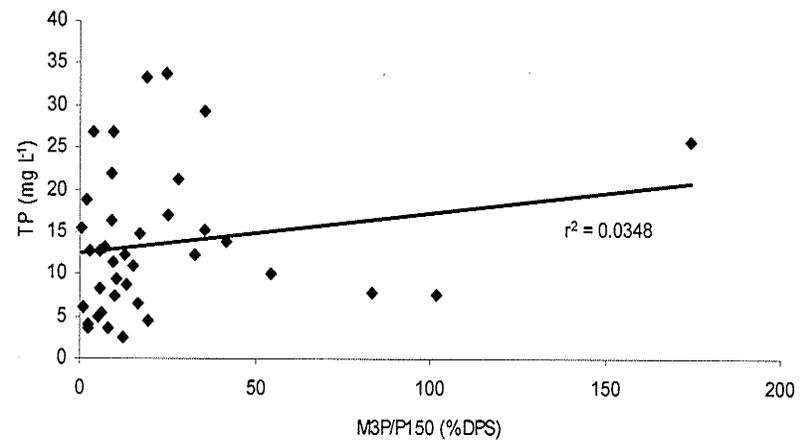
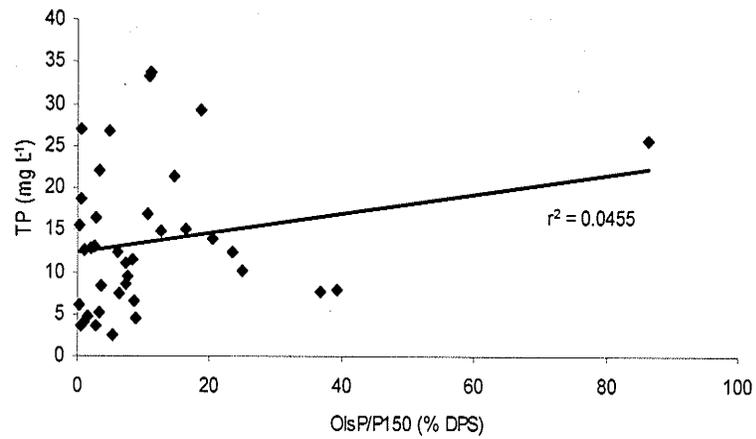


Fig III.4: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) in the first 30 minutes of runoff.

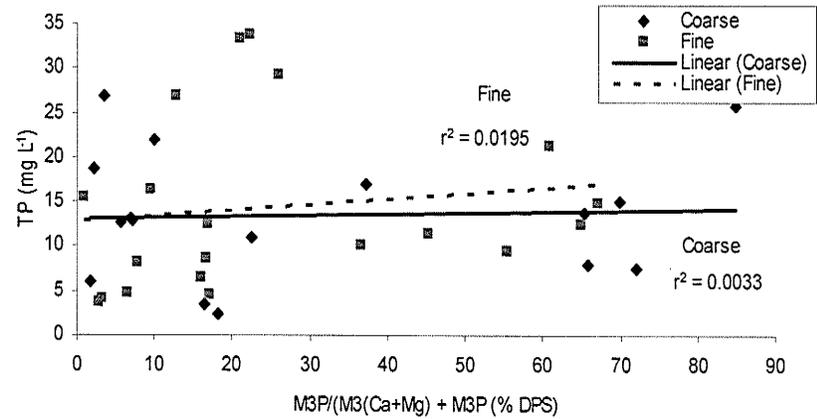
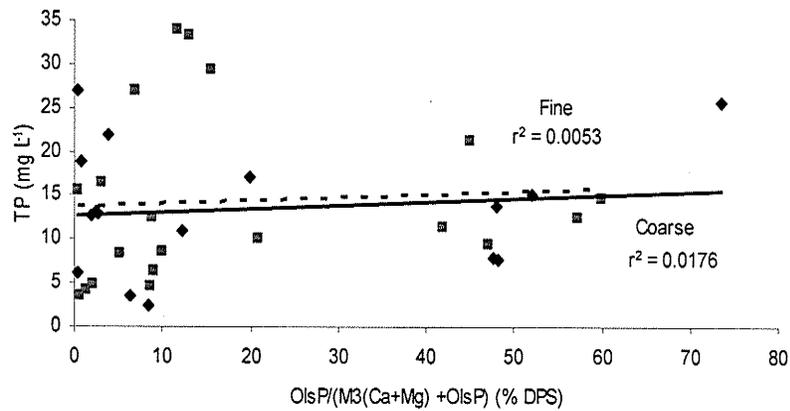
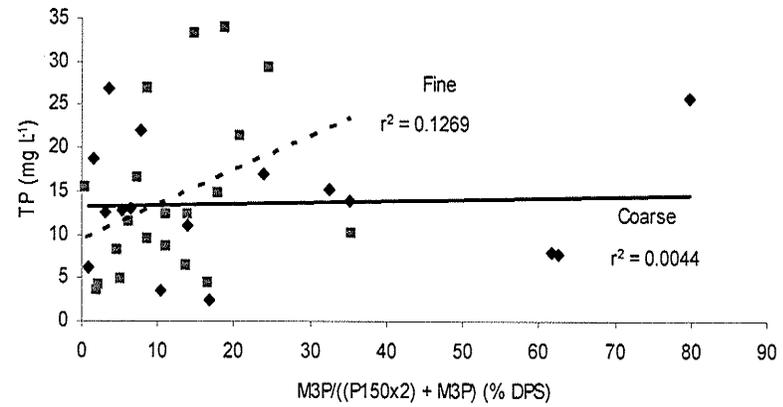
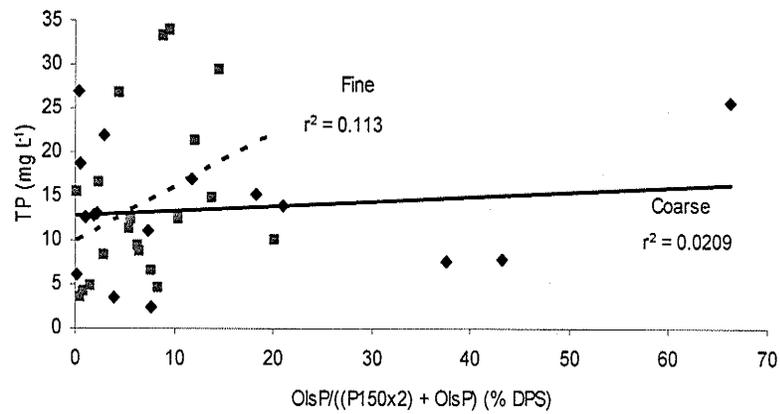


Fig III.5: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

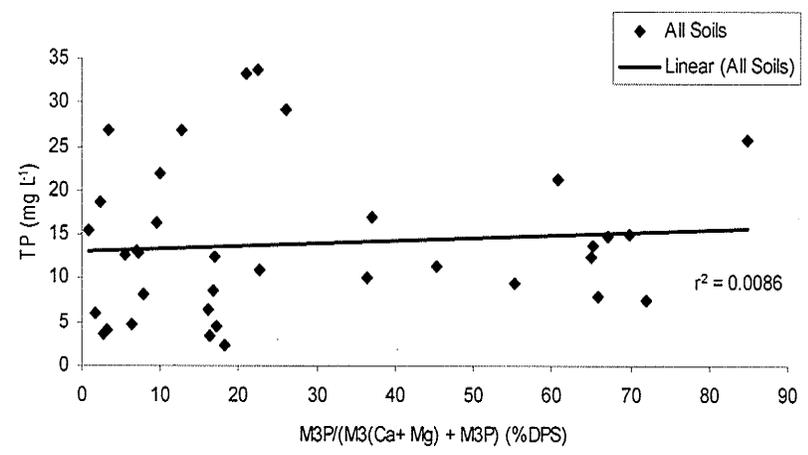
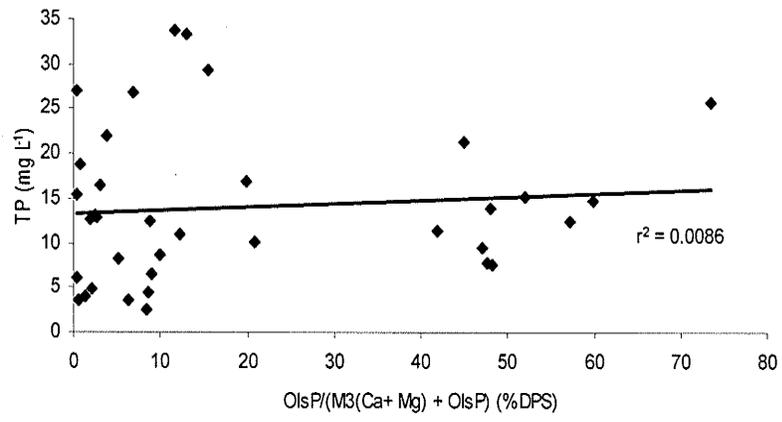
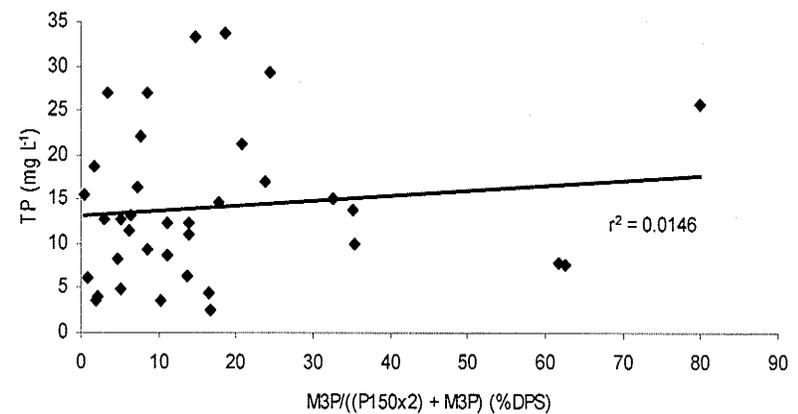
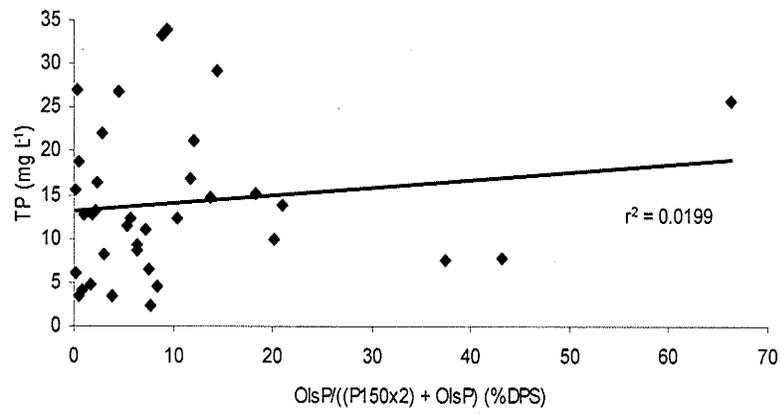


Fig III.6: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) in the first 30 minutes of runoff.

Table III.1: Linear regression for concentration of total P (TP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-30 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0245	12.435	0.001	0.8836	0.3441	8.765	0.213 *	0.0404	0.225	10.407	0.102	0.0508	0.1829	10.870	0.153 *	0.0126
Olsen (OlsP)	0.0448	11.096	0.066	0.3044	0.082	8.803	0.197	0.0501	0.067	10.045	0.151 *	0.0161	0.0553	10.502	0.194 **	0.0044
Modified Kelowna (MKP)	0.0226	11.601	0.033	0.4680	0.0800	8.126	0.319 *	0.0094	0.057	9.885	0.188 *	0.0065	0.0544	9.968	0.243 **	0.0012
Mehlich 3 (M3P)	0.0209	11.004	0.064	0.3117	0.0531	7.842	0.253 *	0.0237	0.039	9.571	0.170 *	0.0101	0.0389	9.538	0.215 **	0.0026
OlsP/(P150)	0.092	11.471	0.077	0.2656	0.402	10.790	0.09	0.2001	0.115	12.300	0.046	0.1983	0.146	12.286	0.071	0.0956
M3P/(P150)	0.039	11.546	0.061	0.3237	0.229	10.592	0.101	0.1726	0.048	12.482	0.035	0.2623	0.055	12.750	0.042	0.2068
OlsP/M3(Ca+Mg) α_1 †	0.058 †	12.306	0.087	0.2866	0.011	14.104	0.001	0.9185	0.041 ¶	13.196	0.020	0.4253	0.071	12.866	0.077	0.1013
M3P/M3(Ca+Mg) α_1	0.025 †	12.404	0.067	0.3534	0.022	13.682	0.005	0.766	0.022 ¶	13.190	0.021	0.4171	0.035	13.090	0.054	0.1734
OlsP/((2xP150)+OlsP)	0.075	11.742	0.036	0.4493	0.616	9.972	0.113	0.1472	0.101	12.578	0.024	0.3448	0.151	12.413	0.056	0.1413
M3P/((2xP150)+M3P)	0.039	11.904	0.017	0.6102	0.4	9.479	0.127	0.1237	0.067	12.472	0.02	0.3947	0.096	12.389	0.039	0.2204
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0373 †	12.904	0.016	0.6563	0.036	13.695	0.005	0.7594	0.035 ¶	13.374	0.008	0.6082	0.075	12.967	0.038	0.2481
M3P/(M3(Ca+Mg) α_2 + M3P)	0.0124 †	13.306	0.003	0.8553	0.062	12.768	0.02	0.5569	0.030 ¶	13.219	0.008	0.6041	0.058	12.837	0.0303	0.3025

*, **, *** significance at p < 0.05, p < 0.01, p < 0.001

† n=16
‡ $\alpha_1 = 0.2$
§ $\alpha_2 = 0.1$
¶ n=36

Appendix IV: STP and DPS regressions with TDP for 30- 60 minute interval

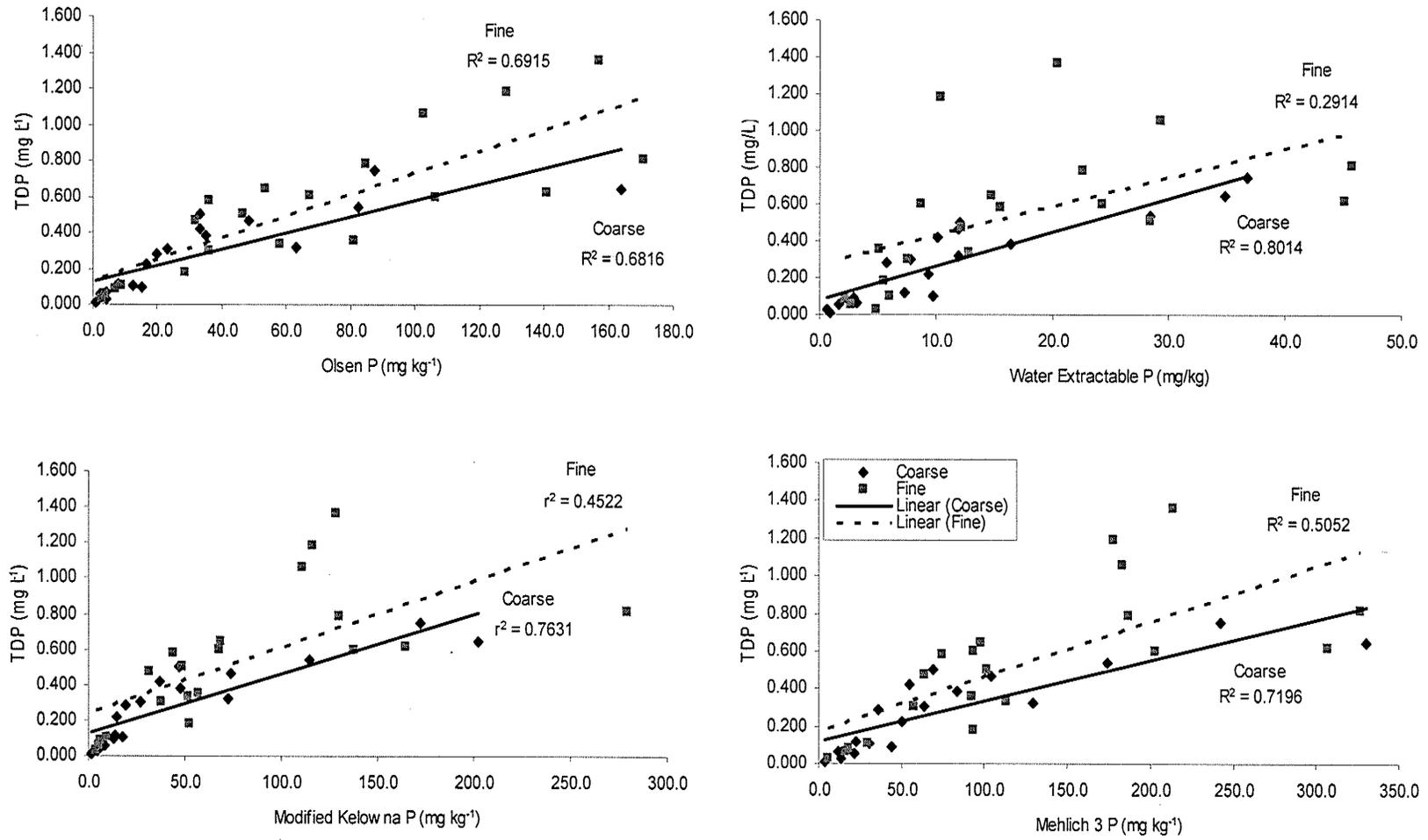


Fig IV.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in 30-60 minutes of runoff.

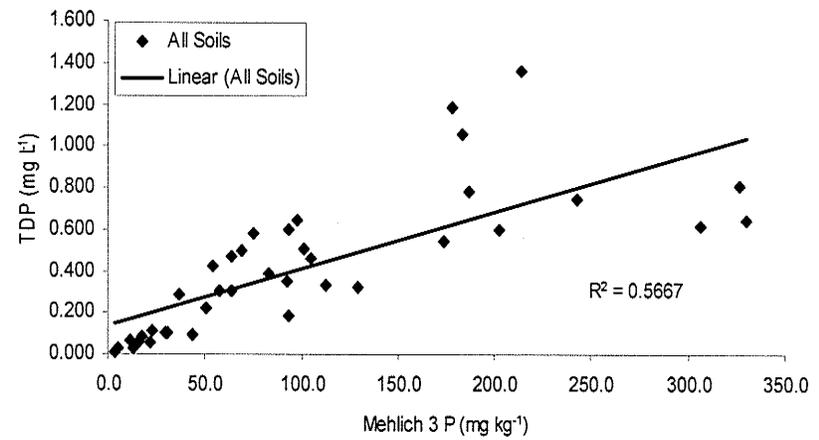
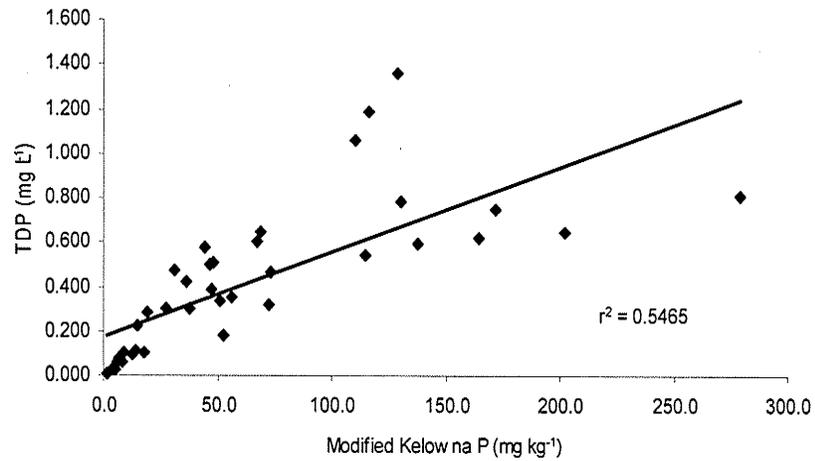
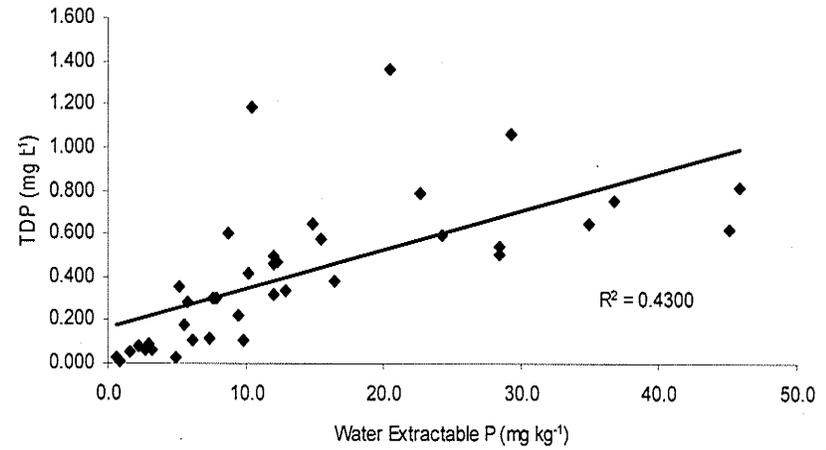
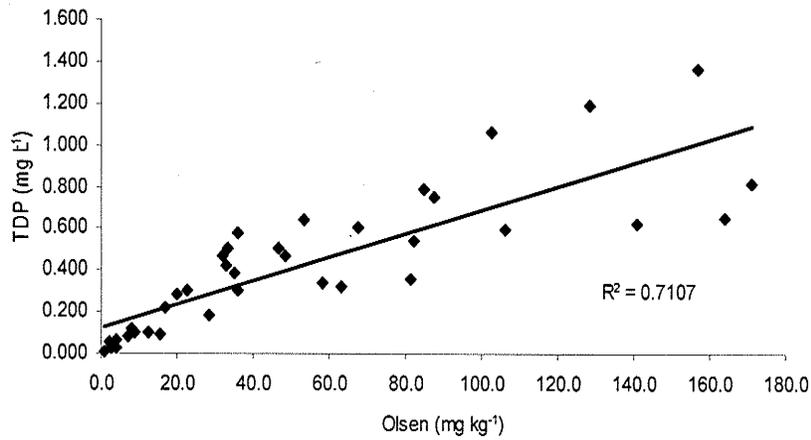


Fig IV.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in 30-60 minutes of runoff.

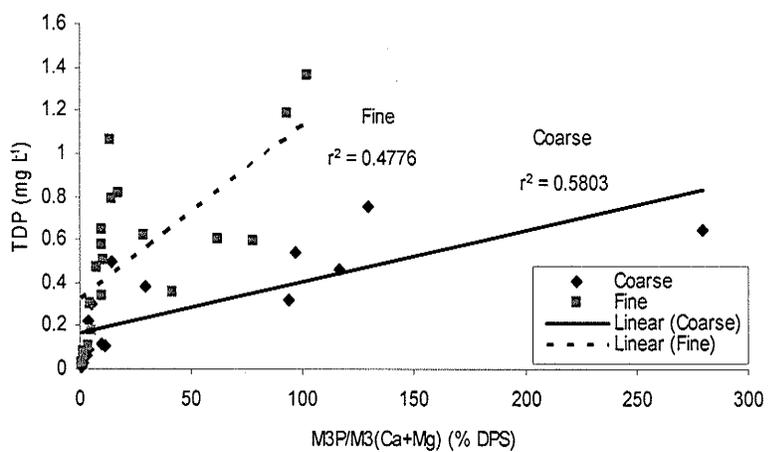
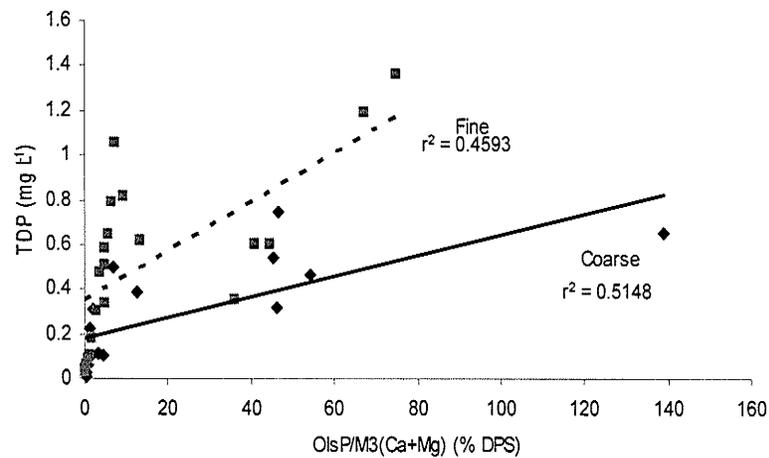
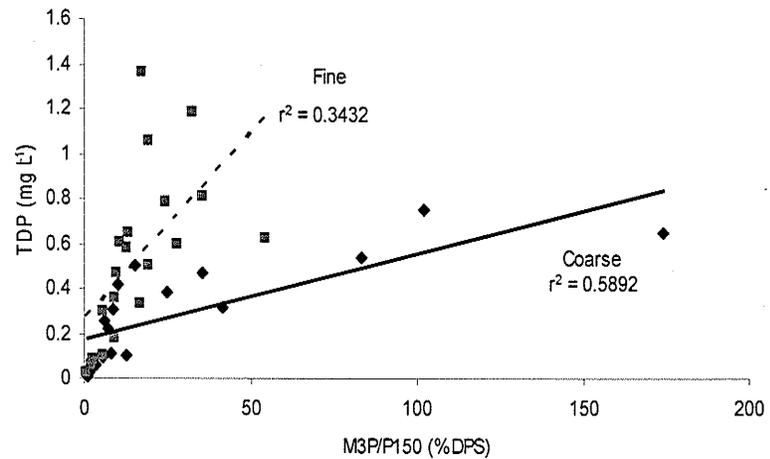
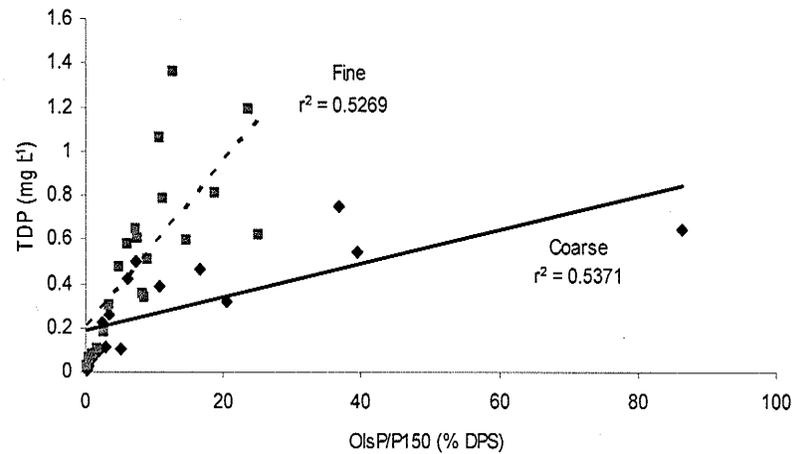


Fig IV.3: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) for the 30-60 minutes of runoff.

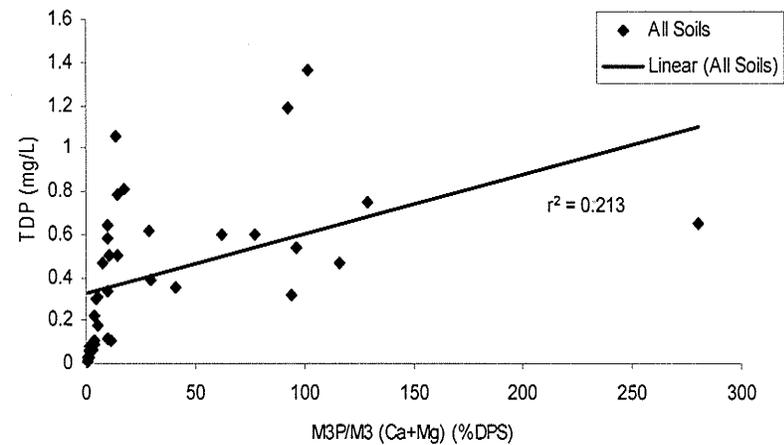
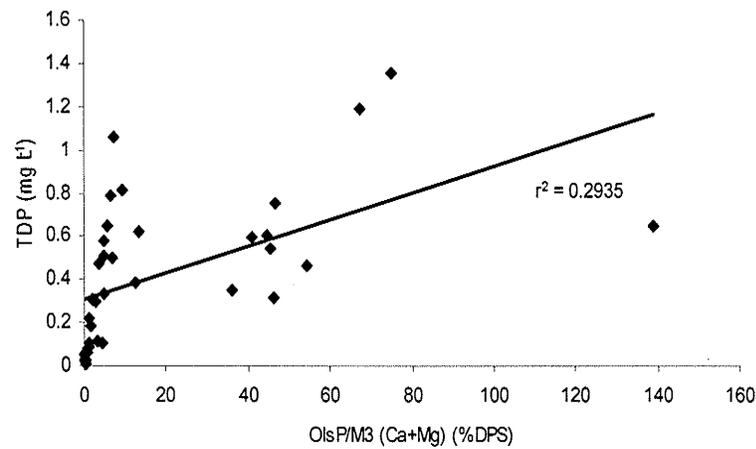
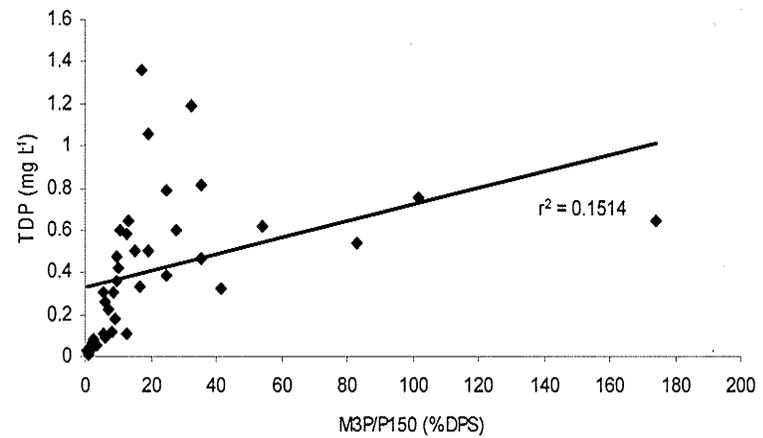
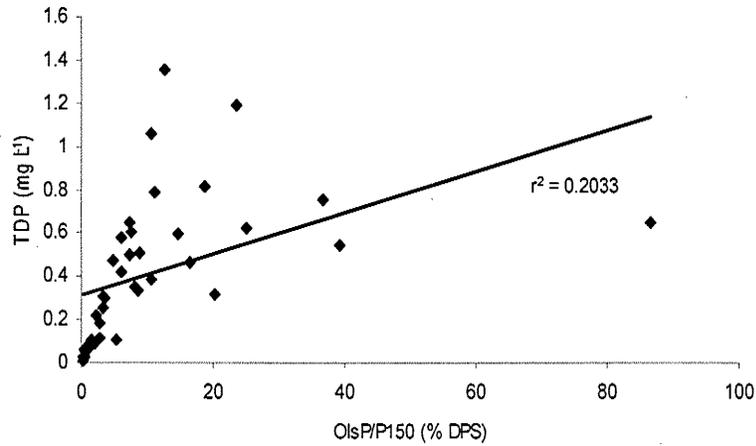


Fig IV.4: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) for the 30-60 minutes of runoff.

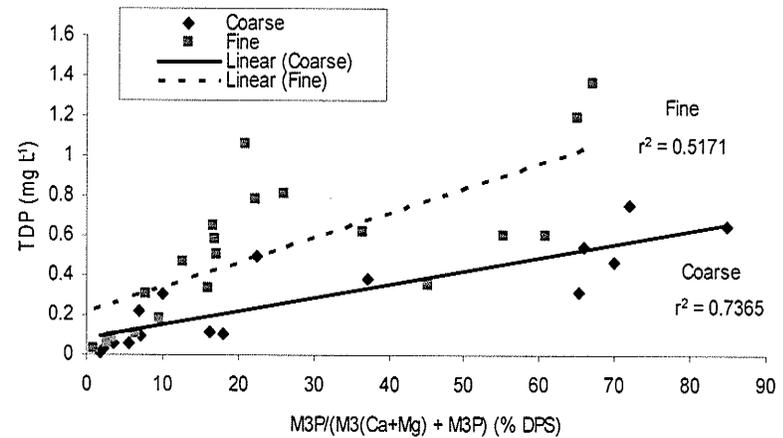
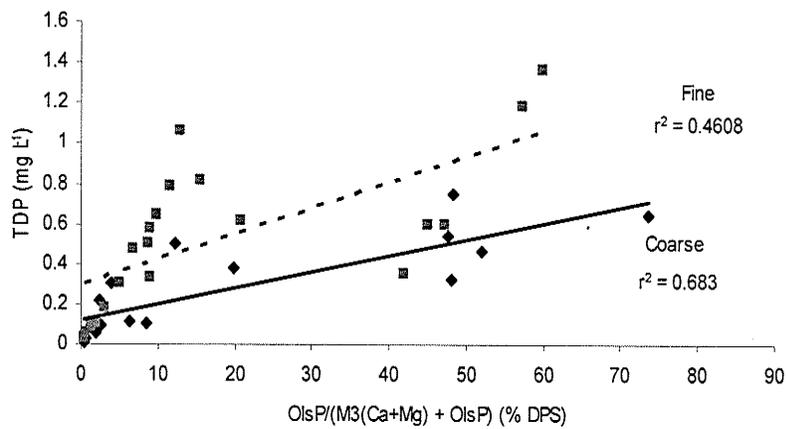
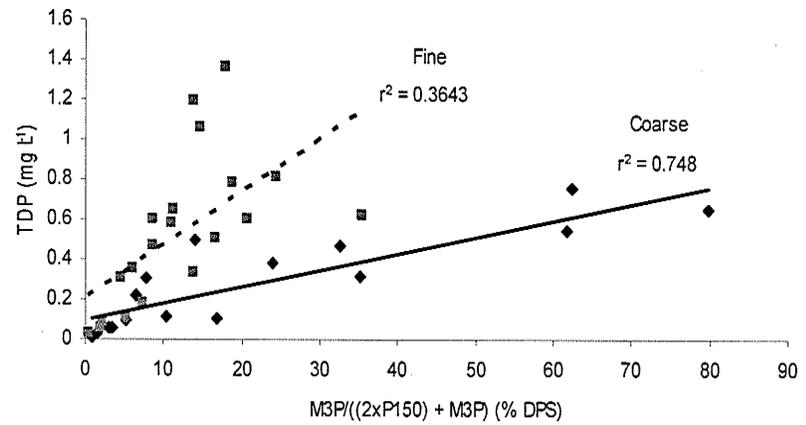
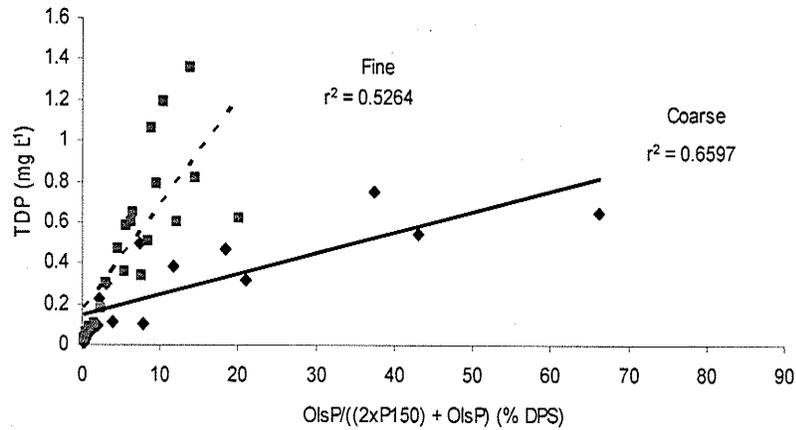


Fig IV.5: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) for the 30-60 minutes of runoff.

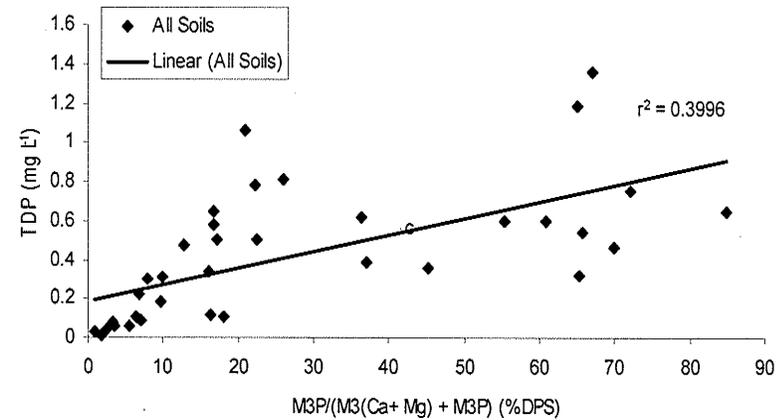
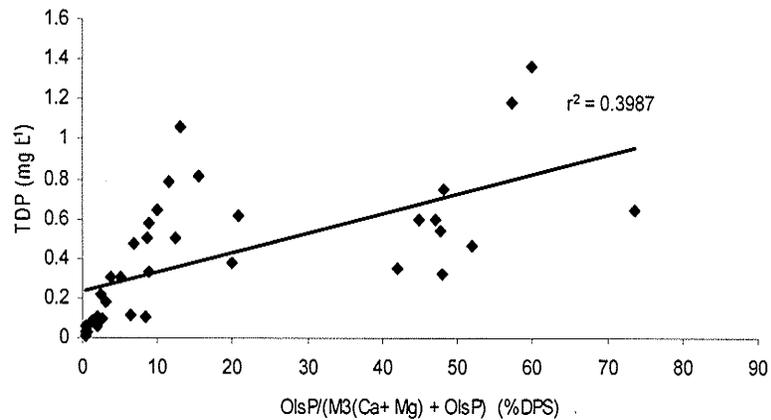
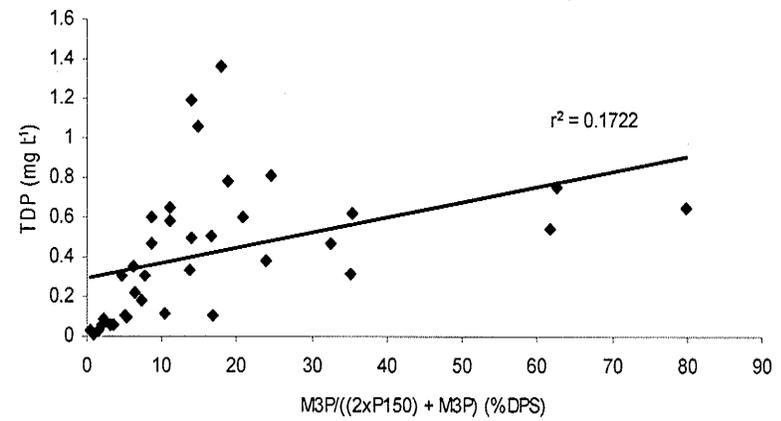
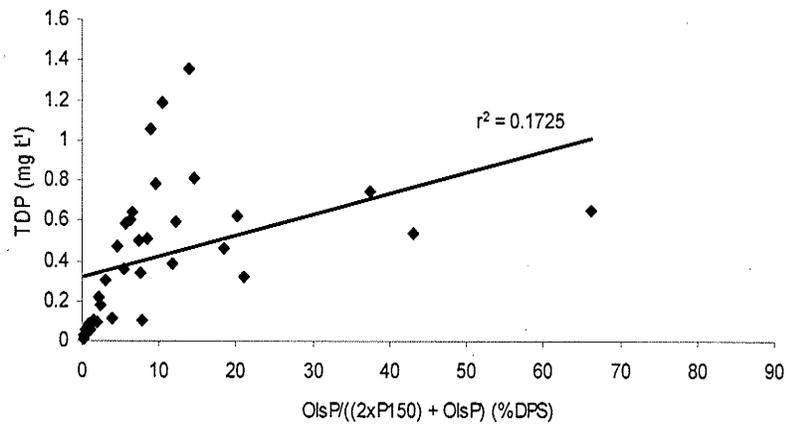


Fig IV.6: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) for the 30-60 minutes of runoff.

Table IV.1: Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 30-60 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0184 a	0.0770	0.80 ***	<0.0001	0.0152 a	0.2791	0.29 *	0.0140	0.0180	0.1655	0.43 ***	<0.0001	0.0203	0.1372	0.701 **	<0.0001
Olsen (Ols-P)	0.0045 a†	0.1305	0.68 ***	<0.0001	0.0060 a	0.1288	0.69 ***	<0.0001	0.0057	0.1203	0.71 ***	<0.0001	0.0060	0.1058	0.849 **	<0.0001
Modified Kelowna (MK-P)	0.0034 a	0.1265	0.76 ***	<0.0001	0.0037 a	0.2450	0.45 **	0.0012	0.0038	0.1741	0.55 ***	<0.0001	0.0048	0.1280	0.714 **	<0.0001
Mehlich 3 (M3-P)	0.0022 a	0.1139	0.72 ***	<0.0001	0.0029 a	0.0178	0.50 **	0.0011	0.0028	0.1344	0.57 ***	<0.0001	0.0036	0.0748	0.678 **	<0.0001
Ols-P/(P150)	0.0076 a	0.1892	0.54 ***	0.0005	0.0379 b	0.1973	0.53 ***	0.0003	0.0095	0.3136	0.20 ***	0.0045	0.0142	0.3178	.253 **	0.0010
M3-P/(P150)	0.0038 a	0.1783	0.59 ***	0.0002	0.0165 b	0.2634	0.34 **	0.0066	0.0039	0.3297	0.15 *	0.0157	0.0049	0.3735	0.124 *	0.0257
Ols-P/M3(Ca+Mg) α_1 ‡	0.0048 a§	0.1571	0.60 ***	0.0007	0.0105 a	0.3776	0.45 **	0.0018	0.0061 ¶	0.3098	0.29 **	0.001	0.0083	0.3172	0.386 ***	<0.0001
M3-P/M3(Ca+Mg) α_1	0.0025 a§	0.1422	0.67 ***	0.0002	0.0077 a	0.3518	0.46 **	0.0014	0.0027 ¶	0.3298	.21 *	0.0068	0.0038	0.3561	0.231 **	0.0030
Ols-P/((2xP150)+Ols-P)	0.0096 a	0.1667	0.61 ***	0.0001	0.0517 b	0.1657	0.53 ***	0.0003	0.0105	0.3152	0.18 **	0.0088	0.0166	0.3102	0.251 **	0.0010
M3-P/((2xP150)+M3-P)	0.0078 a	0.1288	0.68 ***	<0.0001	0.0263 b	0.2121	0.36 **	0.0048	0.0078	0.2918	0.18 **	0.0089	0.0112	0.2976	0.195 *	0.0043
Ols-P/(M3(Ca+Mg) α_2 + Ols-P) #	0.0080 a§	0.1217	0.68 ***	<0.0001	0.0129 a	0.2967	0.46 ***	0.0010	0.0099 ¶	0.2316	0.40 ***	<0.0001	0.0132	0.2250	0.421 ***	<0.0001
M3-P/(M3(Ca+Mg) α_2 + M3-P)	0.0068 a§	0.0804	0.74 ***	<0.0001	0.0124 a	0.2166	0.52 ***	0.0004	0.0084 ¶	0.1898	0.40 ***	<0.0001	0.0108	0.1827	0.372 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0058 a‡‡	0.1464	0.64 ***	0.0001	0.0252 b	0.1492	0.54 ***	0.0002	0.0071 §§	0.2838	0.22 **	0.0033	0.0097	0.2983	0.219 **	<0.0026
WEP/(PSI+WEP) ††	0.0075 ‡‡	0.1765	0.60 ***	0.0003	0.0339	0.3719	0.150	0.0871	0.0057 §§	0.3652	0.080	0.0939	0.0132	0.3326	0.352 ***	<0.0001
MK-P/(PSI+MK-P) ††	0.0056 a‡‡	0.1365	0.65 ***	<0.0001	0.0192 b	0.2122	0.42 **	0.0020	0.0065 §§	0.2813	0.21 **	0.004	0.0109	0.2303	0.400 ***	<0.0001
M3-P/(PSI+M3-P) ††	0.0057 a‡‡	0.0989	0.66 ***	<0.0001	0.0162 b	0.1465	0.43 **	0.0017	0.0069 §§	0.2273	0.25 **	0.0018	0.0109	0.1593	0.398 ***	<0.0001

*, **, *** significance at p < 0.05, p < 0.01, p < 0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p < 0.05

‡ $\alpha_1 = 0.2$

§ n=16

¶ n=36

$\alpha_2 = 0.1$

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Appendix V: STP and DPS regressions with PP for 30- 60 minute interval

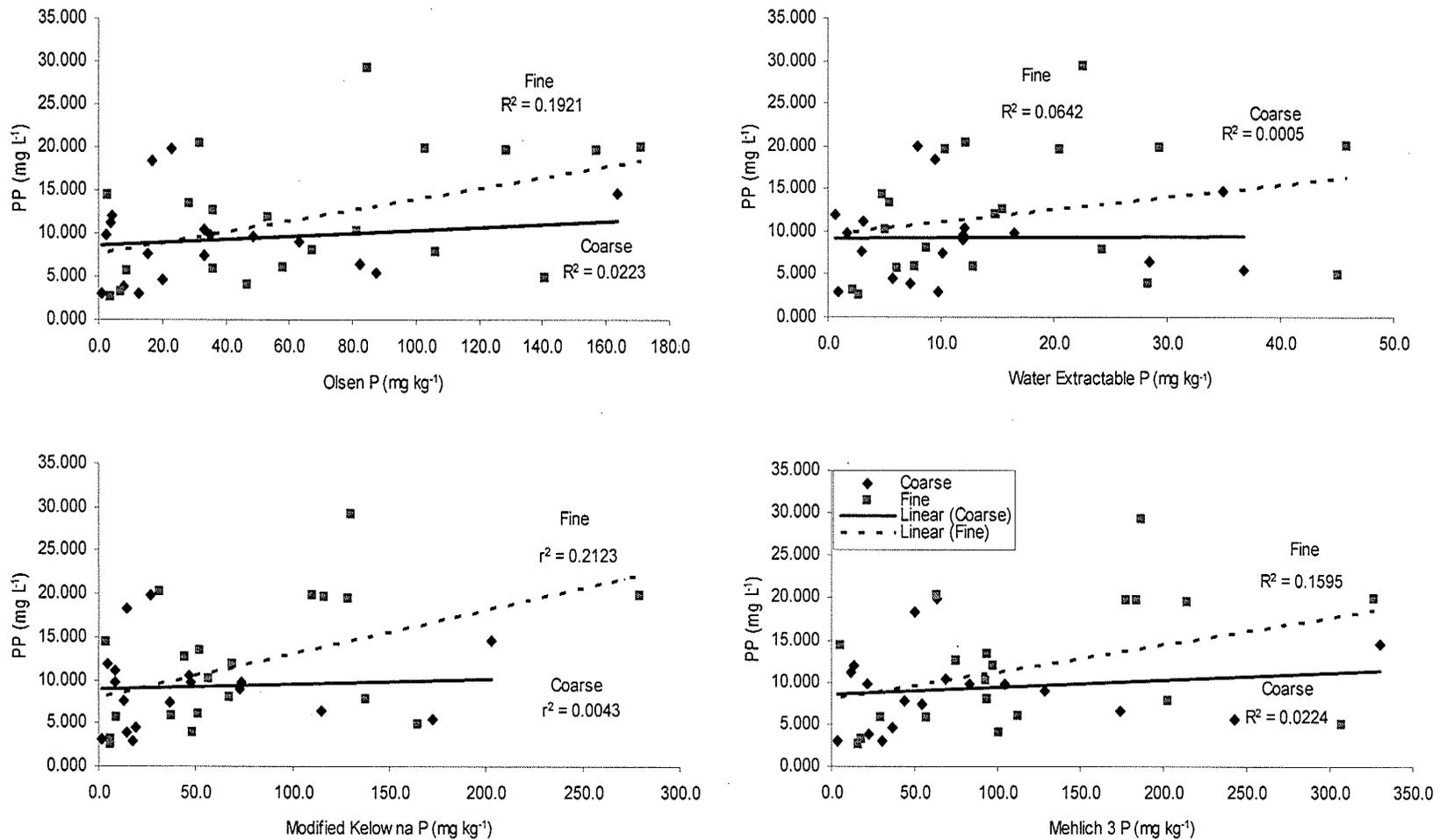


Fig V.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 30-60 minutes of runoff.

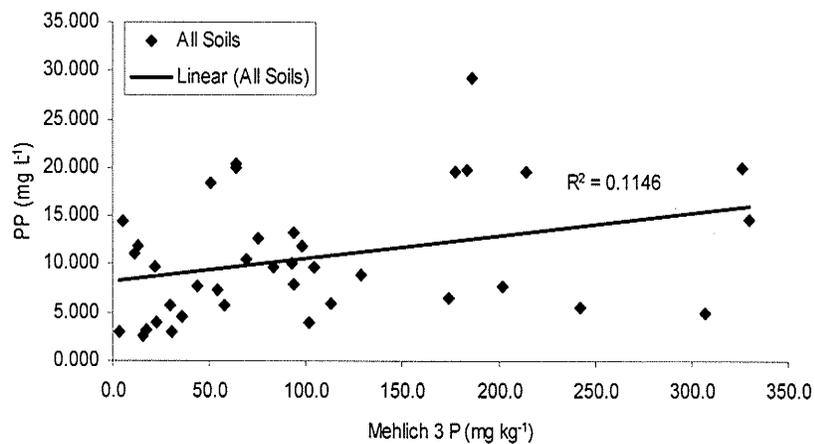
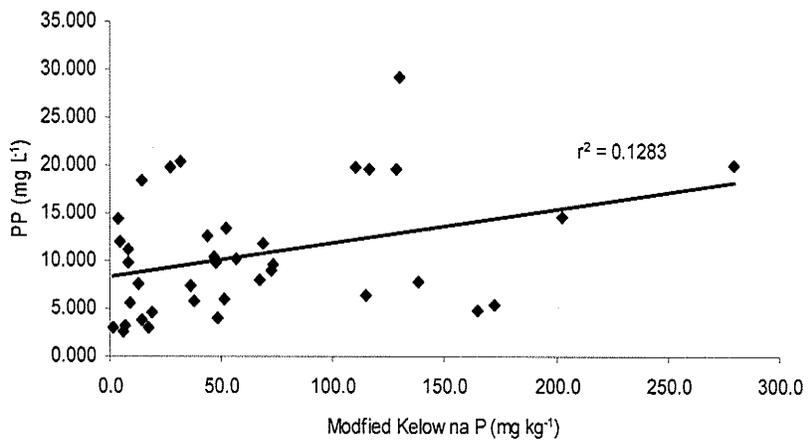
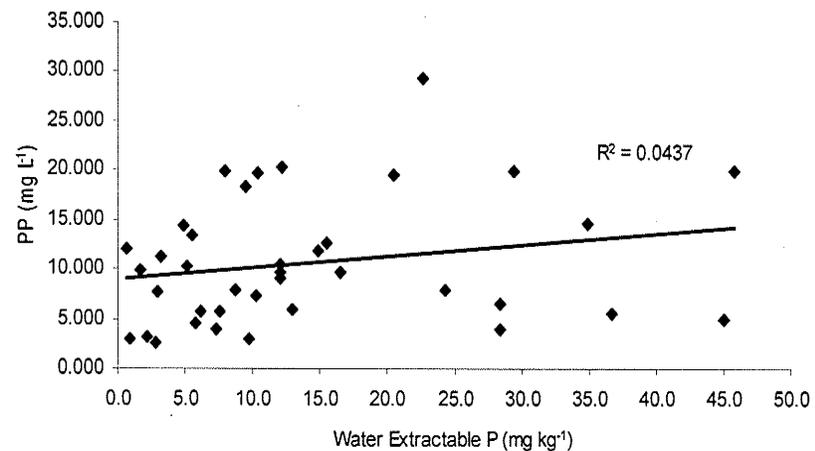
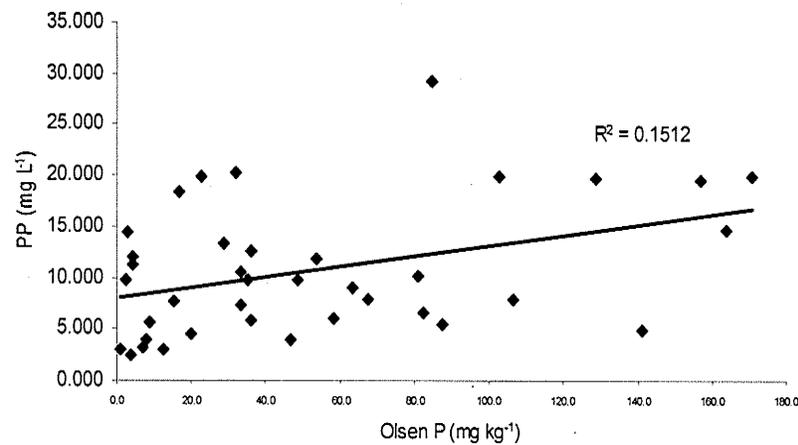


Fig V.2: : Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 30-60 minutes of runoff.

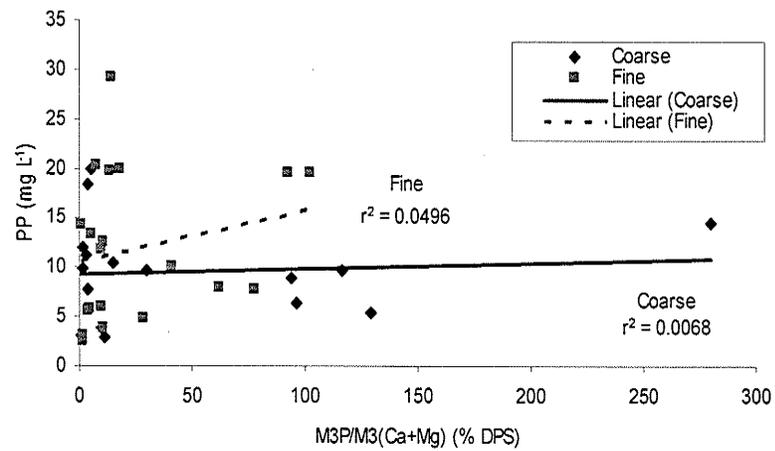
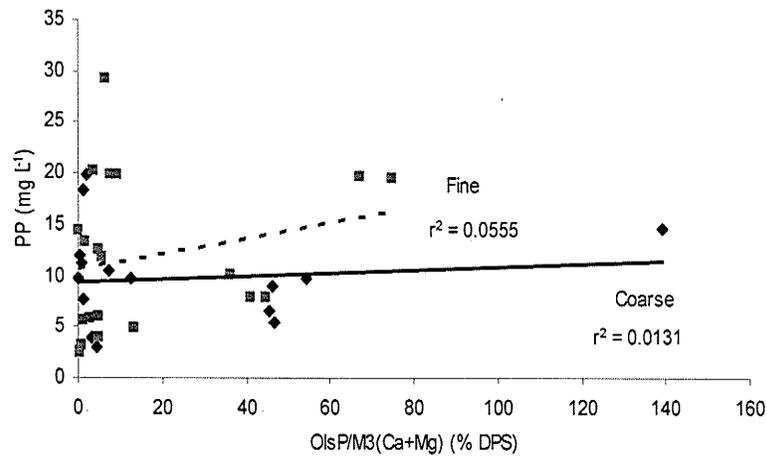
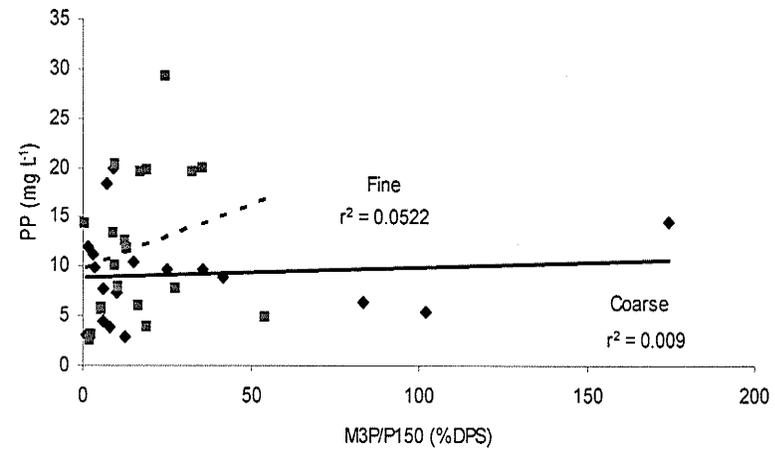
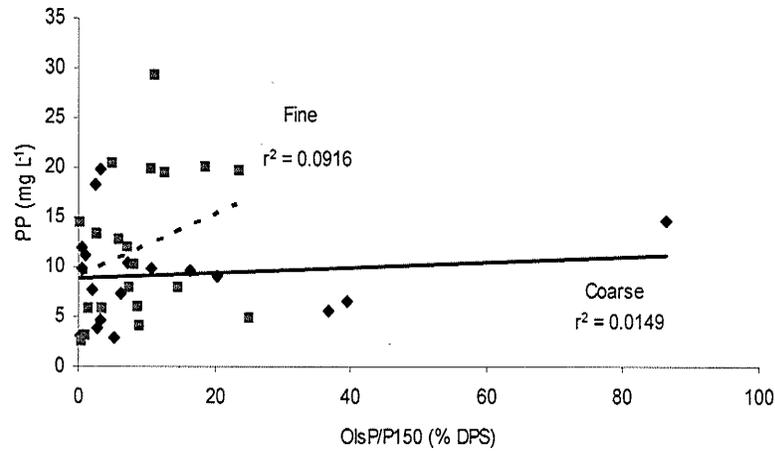


Fig V.3: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) for the 30-60 minutes of runoff.

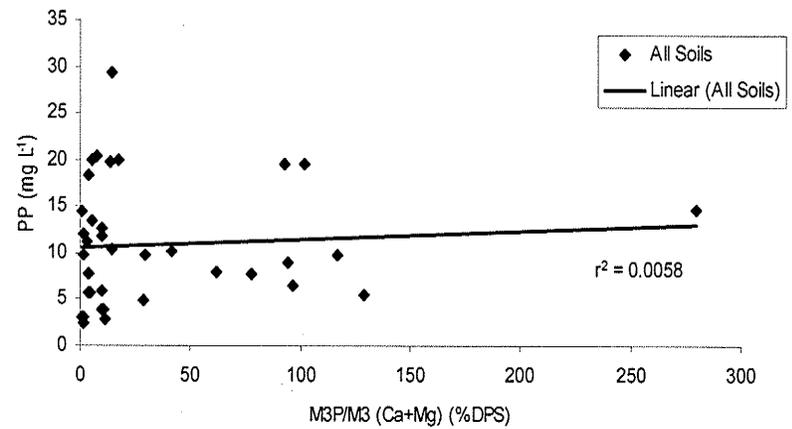
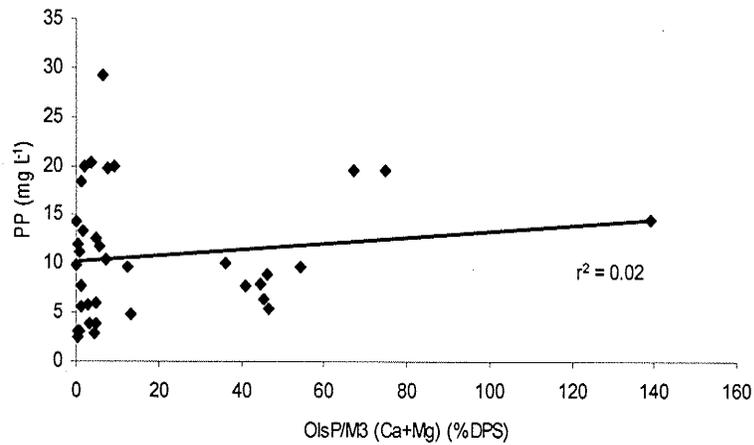
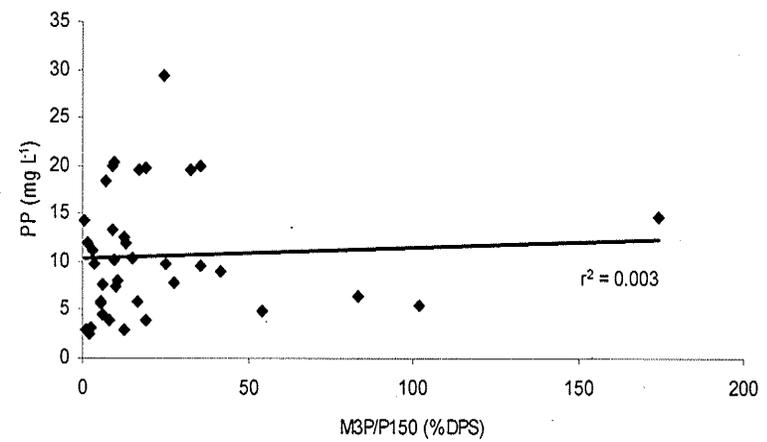
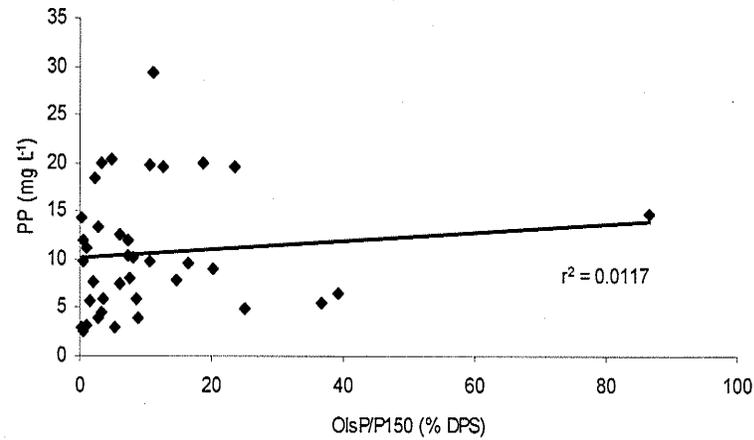


Fig V.4: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods (Ige et al., 2005a) for the 30-60 minutes of runoff.

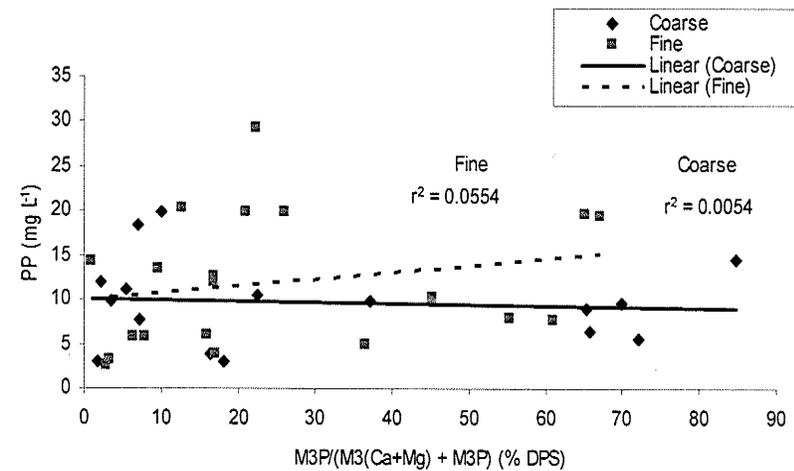
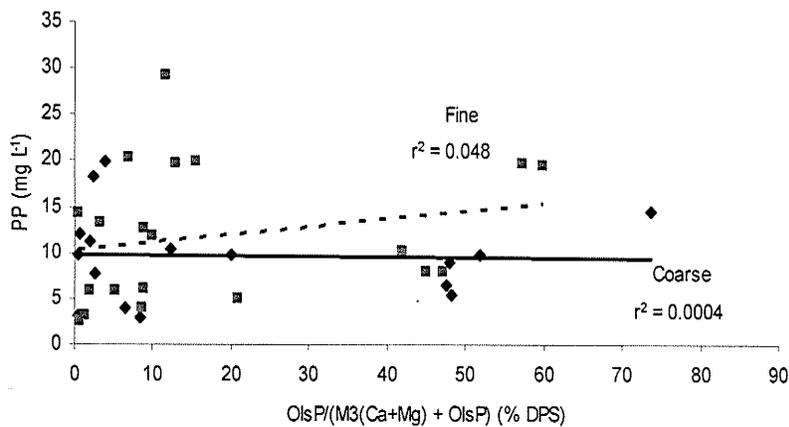
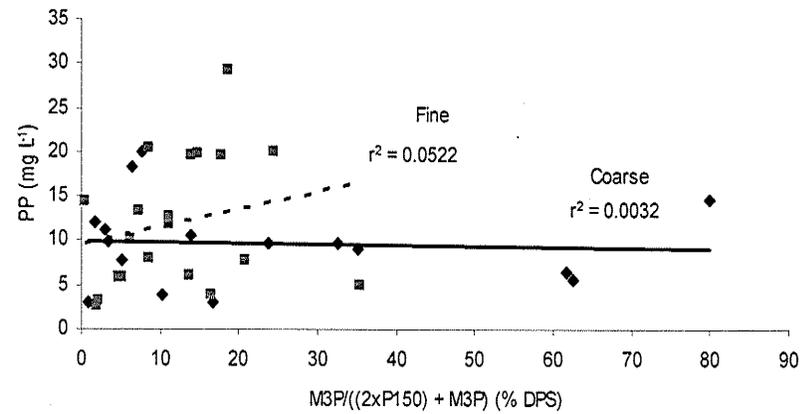
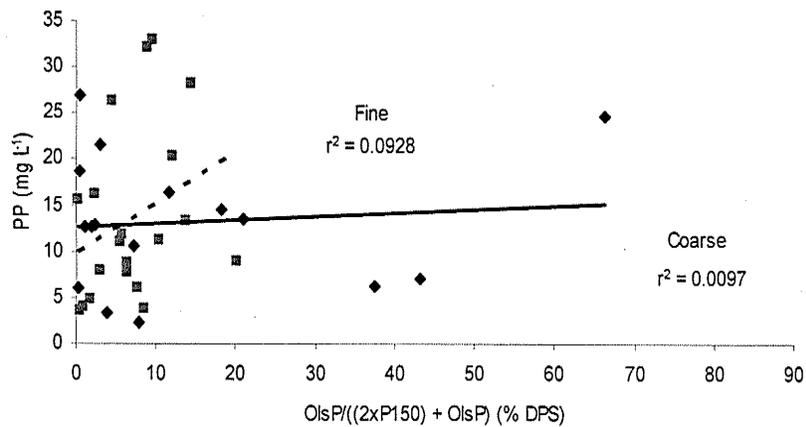


Fig V.5: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) for the 30-60 minutes of runoff.

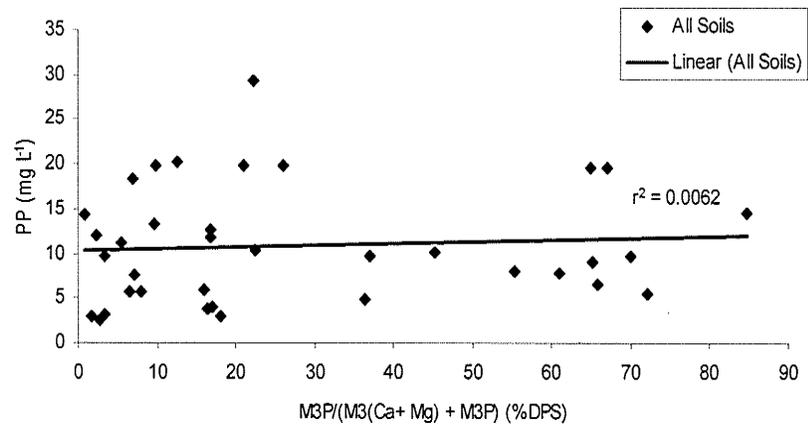
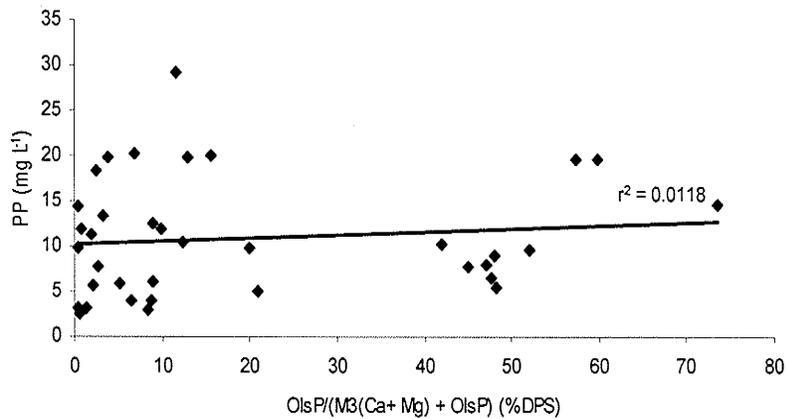
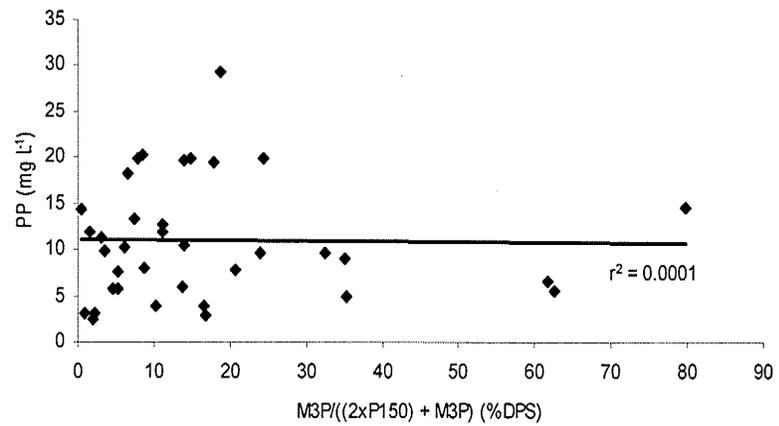
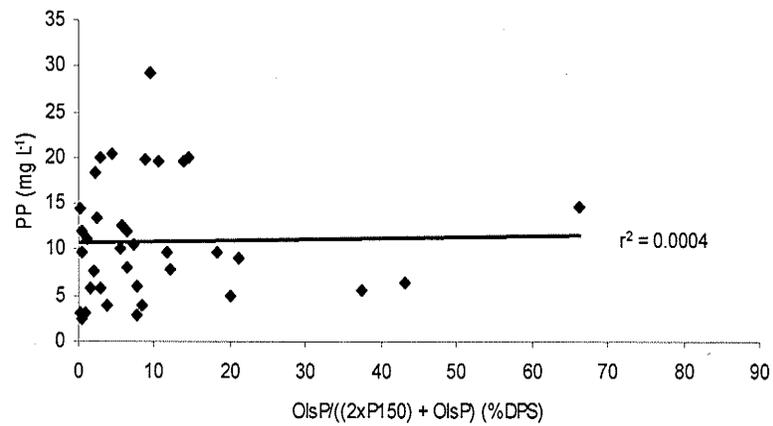


Fig V.6: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium (Akinremi et al., 2007) for the 30-60 minutes of runoff.

Table V.1: Linear regression for concentration of total particulate P (P) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 30-60 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0102	9.088	0.0005	0.9275	0.1452	9.559	0.064	0.2811	0.1104	9.073	0.044	0.2079	0.082	9.428	0.058	0.1333
Olsen (OlsP)	0.0174	8.575	0.0223	0.5542	0.0623	7.702	0.192	0.0532	0.0503	7.975	0.151 *	0.0158	0.034	8.699	0.136 *	0.0191
Modified Kelowna (MKP)	0.0054	8.938	0.0043	0.7953	0.0503	8.014	0.212 *	0.0409	0.0356	8.342	0.128 *	0.0272	0.029	8.692	0.130 *	0.0224
Mehlich 3 (M3P)	0.0082	8.528	0.0224	0.5533	0.0324	7.945	0.159	0.0811	0.0238	8.163	0.115 *	0.0376	0.022	8.299	0.131 *	0.0217
OlsP/(P150)	0.0271	8.839	0.015	0.6290	0.3125	9.147	0.092	0.1946	0.0438	10.146	0.012	0.5183	0.056	10.177	0.020	0.3848
M3P/(P150)	0.0100	8.905	0.009	0.7076	0.1269	9.836	0.052	0.3326	0.0106	10.389	0.003	0.7430	0.014	10.531	0.005	0.6694
OlsP/M3(Ca+Mg) α_1 †	0.016 †	9.176	0.014	0.6699	0.0824	10.354	0.064	0.2962	0.0333 ¶	10.130	0.023	0.3886	0.028	10.396	0.022	0.3887
M3P/M3(Ca+Mg) α_1	0.0057 †	9.261	0.008	0.7544	0.057	10.245	0.059	0.3182	0.0100 ¶	10.427	0.007	0.6273	0.010	10.644	0.008	0.6096
OlsP/((2xP150)+OlsP)	0.0127	9.042	0.002	0.8491	0.3811	9.207	0.0731	0.2488	0.0184	10.450	0.001	0.8194	0.023	10.869	0.003	0.7666
M3P/((2xP150)+M3P)	-0.0001	9.209	0.000	0.9992	0.1972	9.513	0.052	0.3326	0.0245	10.912	0.003	0.7596	0.120	10.644	0.001	0.8341
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	-0.0033 †	9.632	0.0003	0.9538	0.0829	10.407	0.048	0.3536	0.0323 ¶	10.275	0.0117	0.5361	0.034	10.408	0.0148	0.4733
M3P/(M3(Ca+Mg) α_2 + M3P)	-0.0116 †	9.922	0.005	0.8026	0.0803	9.867	0.055	0.3179	0.0198 ¶	10.354	0.0061	0.6553	0.022	10.486	0.008	0.5975
*	significant at p < 0.05															
**	significant at p < 0.005															
***	significant at p < 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix VI: STP and DPS regressions with TP for 30- 60 minute interval

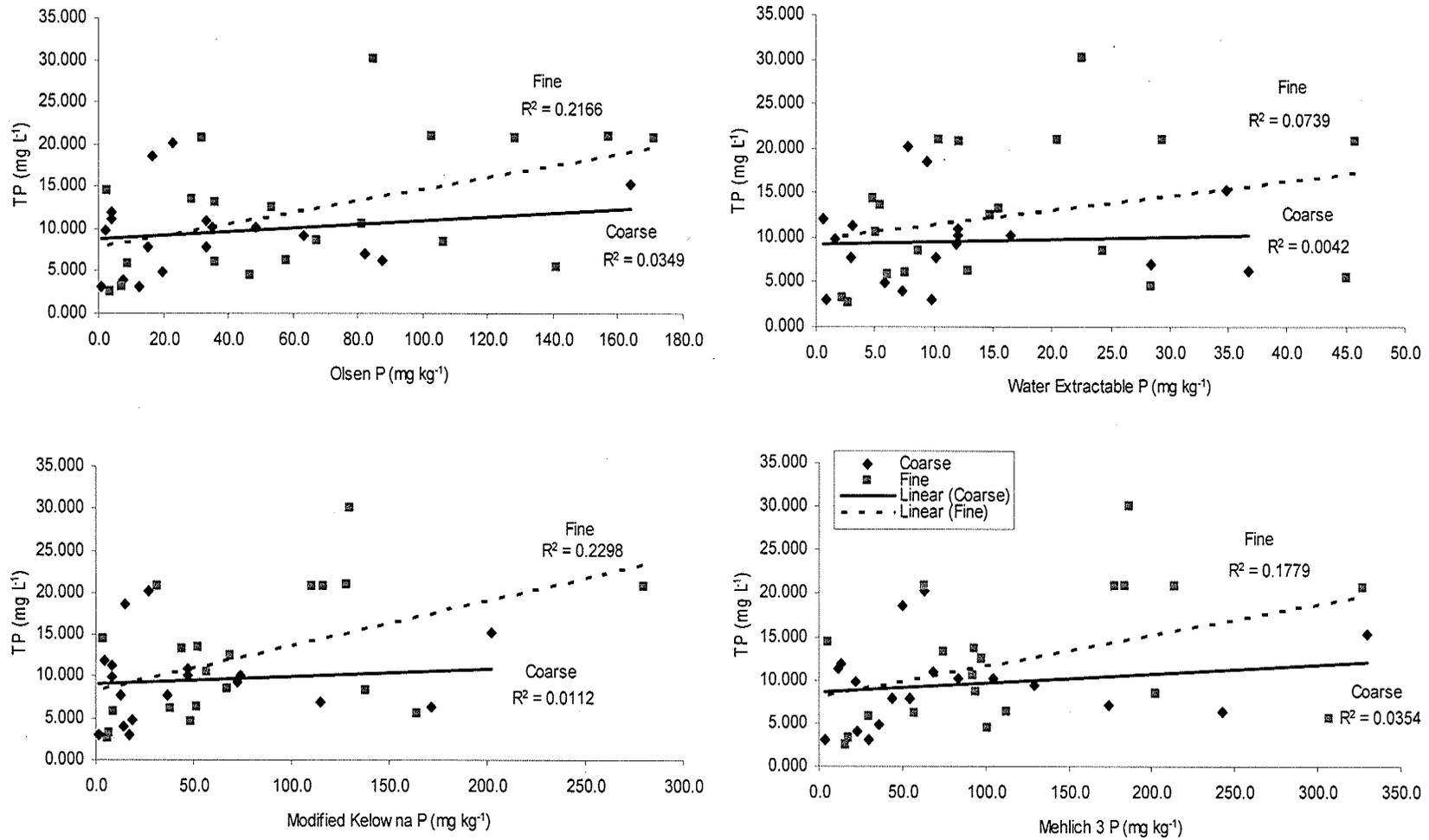


Fig VI.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 30-60 minutes of runoff.

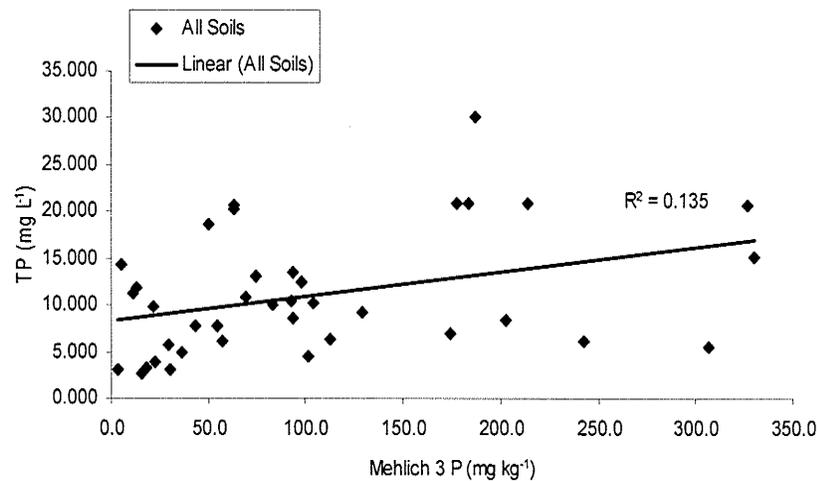
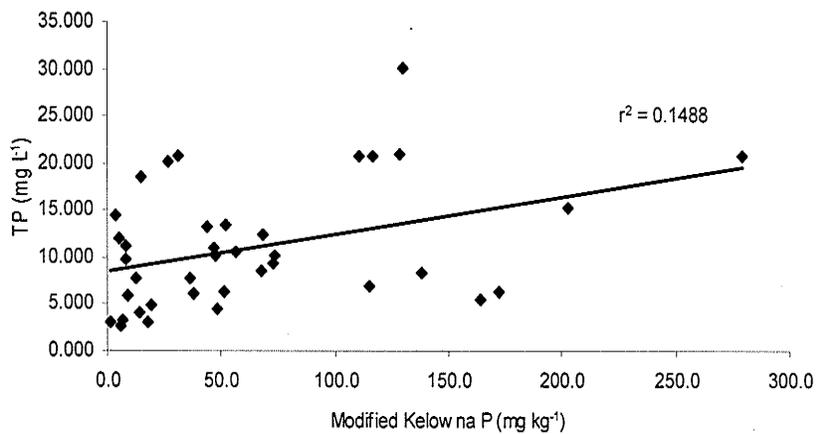
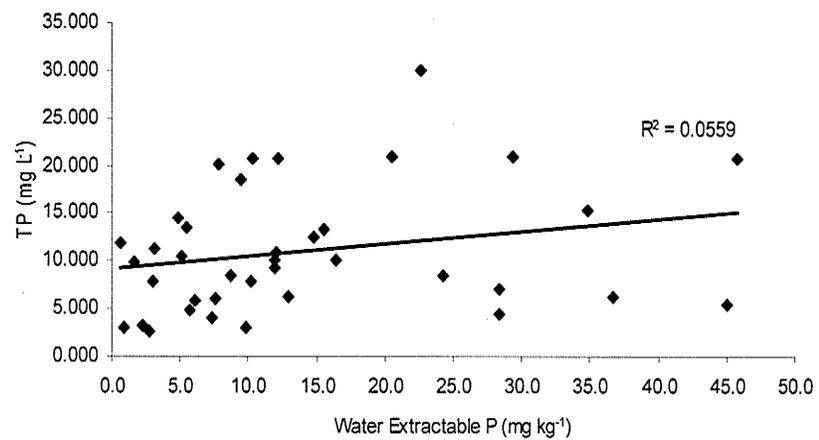
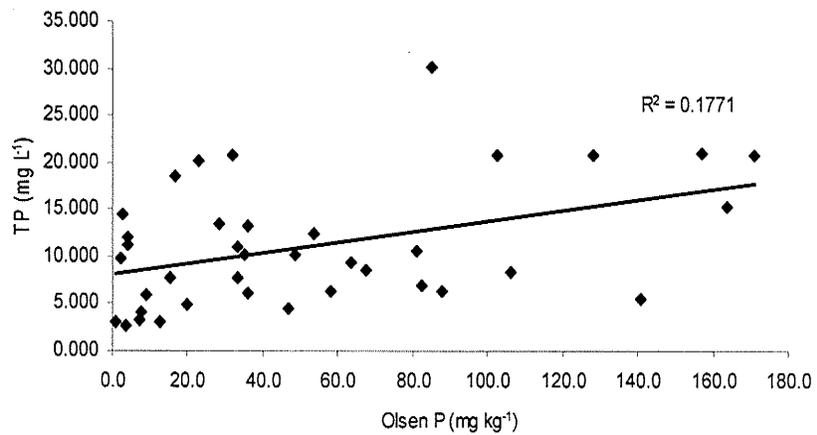


Fig VI.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 30-60 minutes of runoff.

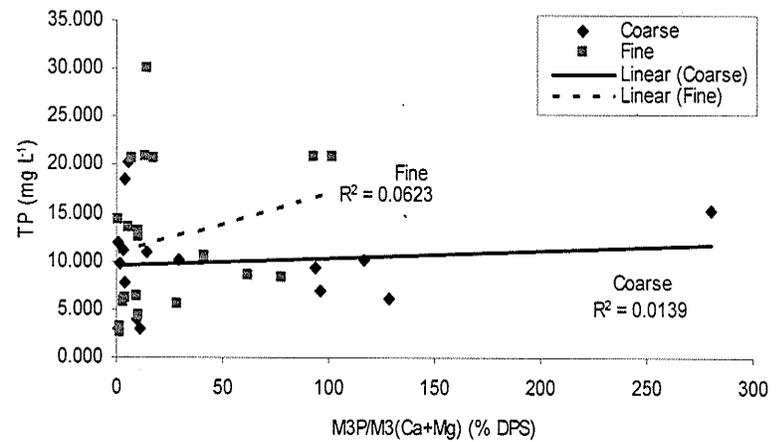
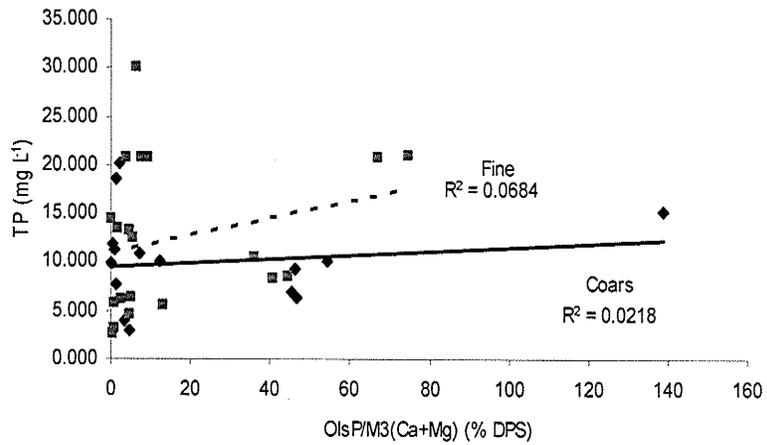
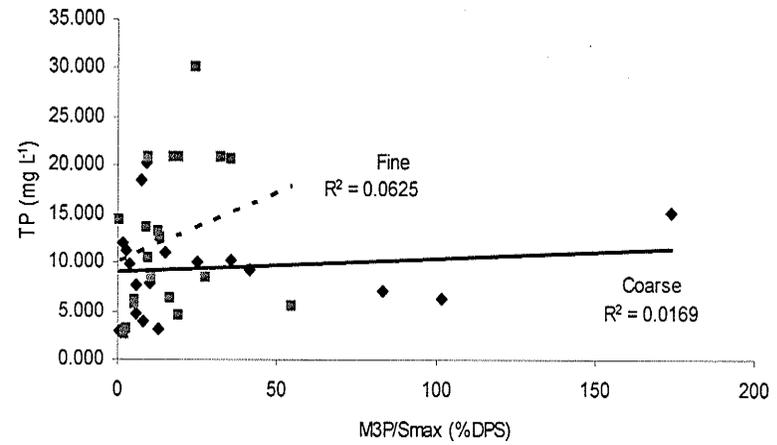
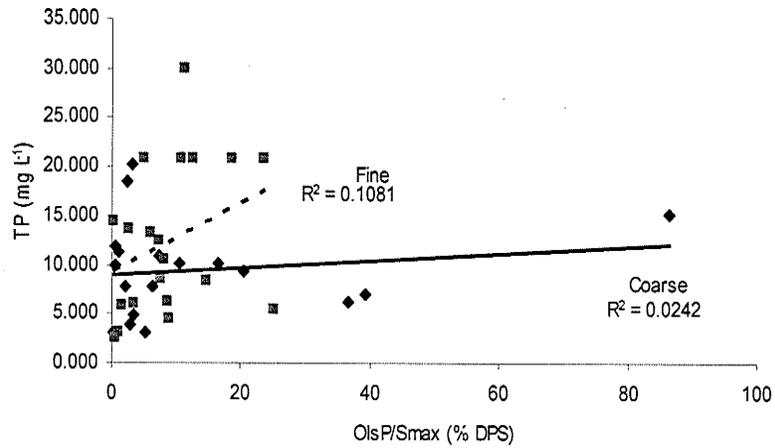


Fig VI.3: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 30-60 minutes of runoff (Ige et al., 2005a).

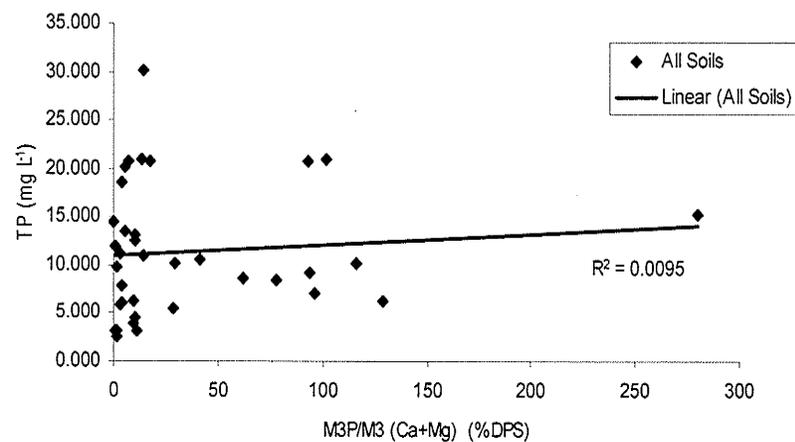
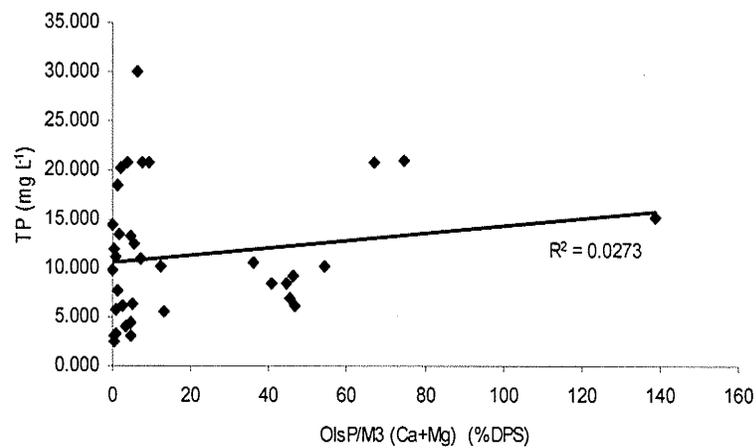
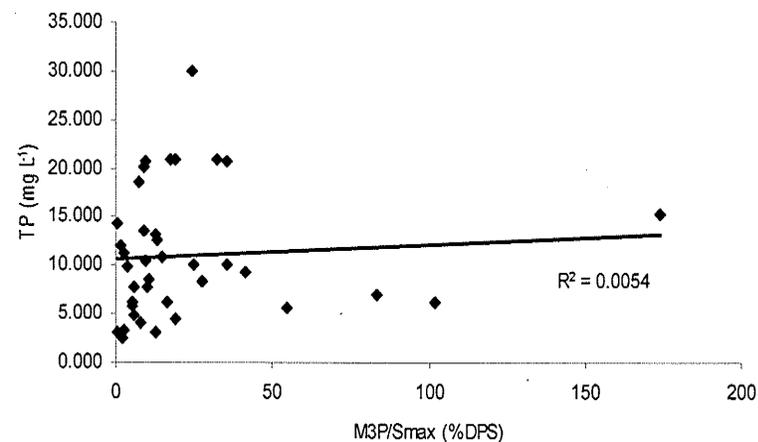
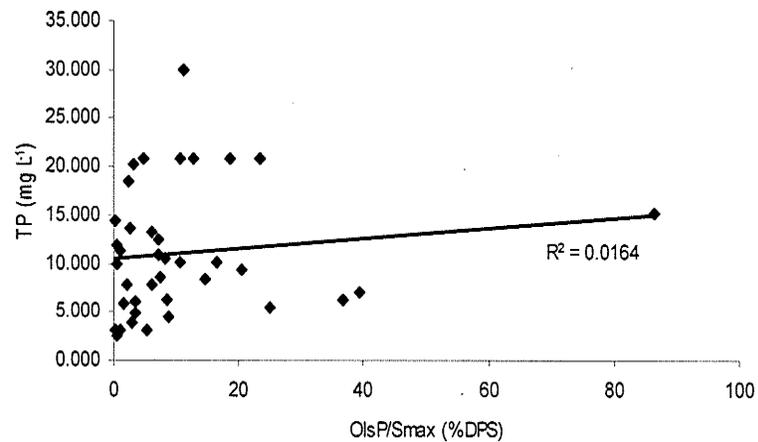


Fig VI.4: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 30-60 minutes of runoff (Ige et al., 2005a).

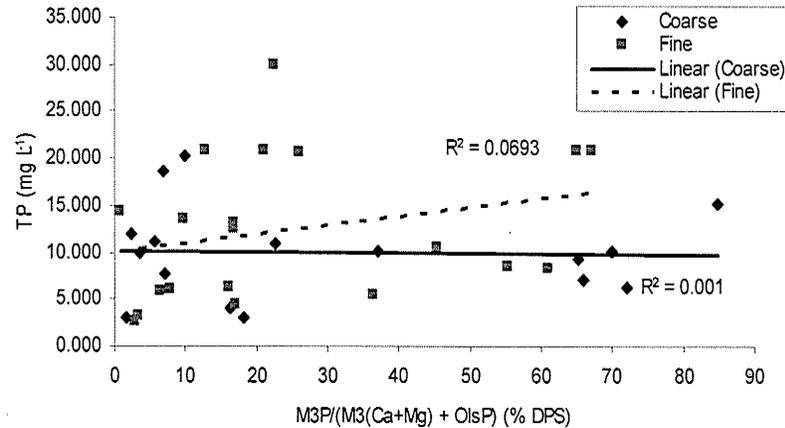
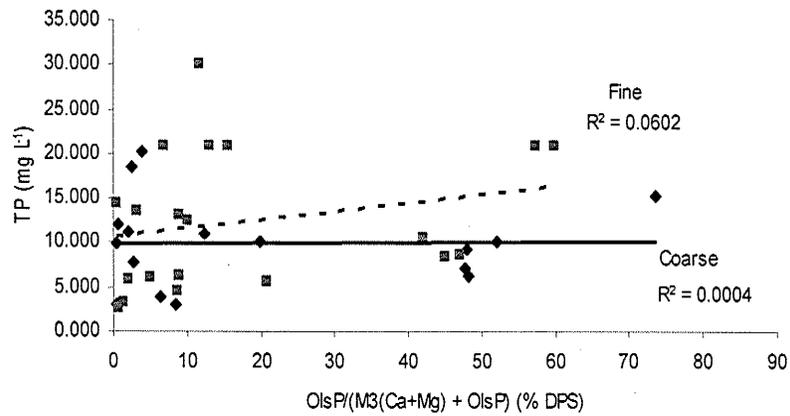
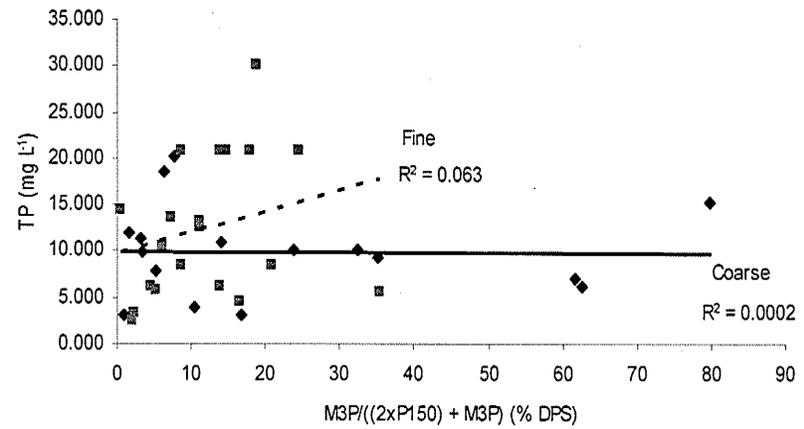
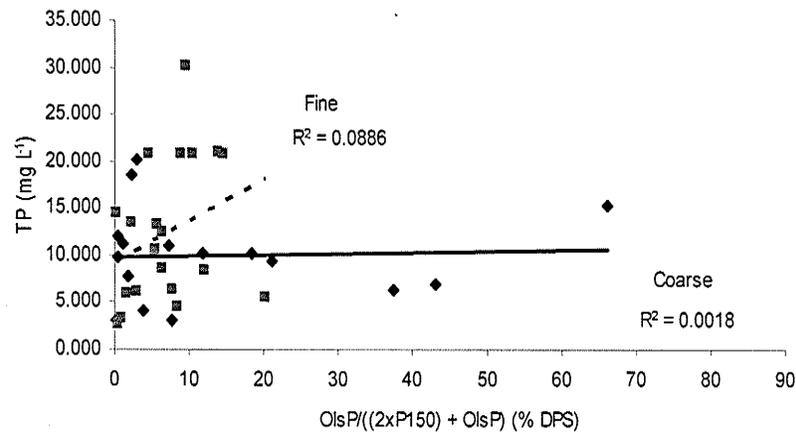


Fig VI.5: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 30-60 minutes of runoff (Akinremi et al., 2007).

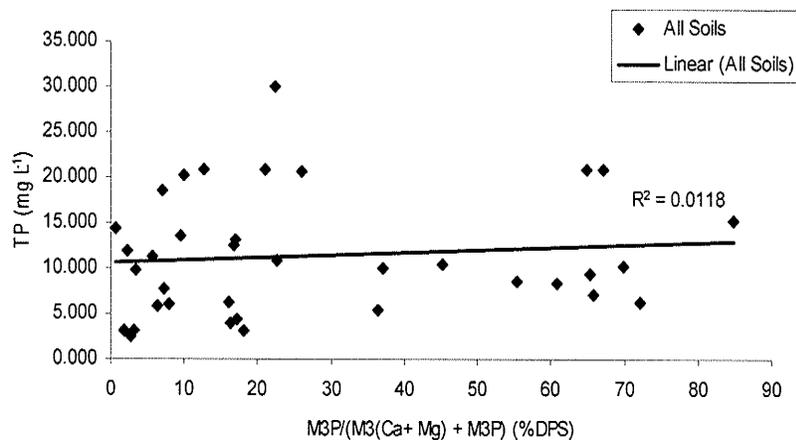
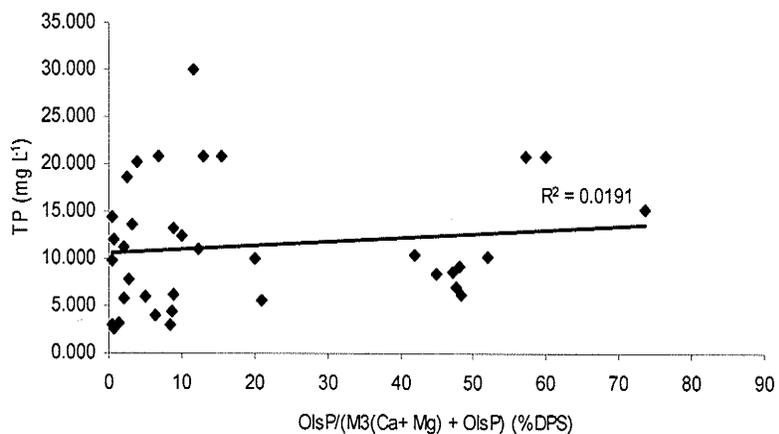
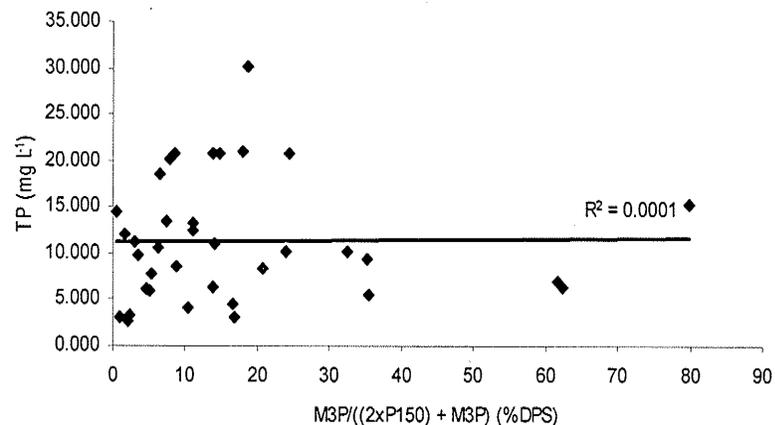
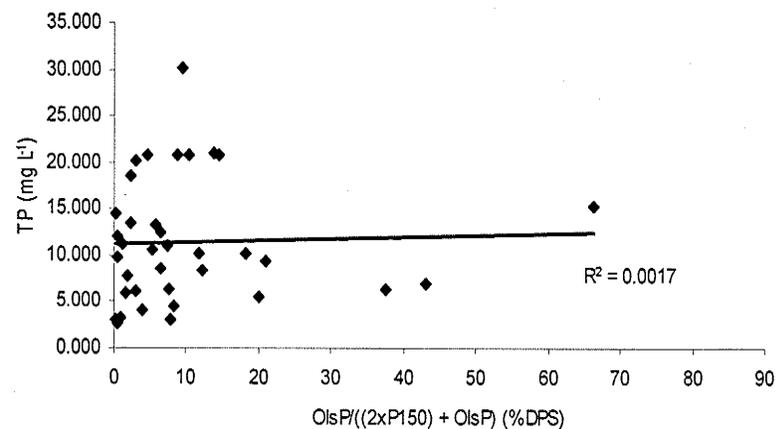


Fig VI.6: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 30-60 minutes of runoff (Akinremi et al., 2007).

Table VI.1: Linear regression for concentration of total P (TP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 30-60 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0286	9.165	0.004	0.7991	0.1608	9.837	0.074	0.2461	0.1284	9.238	0.0559	0.1530	0.1023	9.565	0.085	0.0683
Olsen (OlsP)	0.0219	8.706	0.035	0.4580	0.0683	7.831	0.217 *	0.0387	0.0560	8.095	0.177 *	0.0085	0.0396	8.805	0.176 *	0.0070
Modified Kelowna (MKP)	0.0088	9.064	0.011	0.6756	0.0540	8.259	0.230 *	0.0325	0.0394	8.517	0.149 *	0.0167	0.0336	8.820	0.165 *	0.0093
Mehlich 3 (M3P)	0.0104	8.642	0.035	0.4546	0.0353	8.120	0.178	0.0640	0.0266	8.297	0.135 *	0.0233	0.0256	8.373	0.165 *	0.0092
OlsP/(P150)	0.0347	9.028	0.024	0.5378	0.0350	9.344	0.108	0.1570	0.0533	10.459	0.016	0.4440	0.0701	10.494	0.0293	0.2910
M3P/(P150)	0.0138	9.083	0.017	0.6068	0.1433	10.100	0.625	0.2877	0.0145	10.719	0.005	0.6625	0.0184	10.904	0.008	0.5739
OlsP/M3(Ca+Mg) α_1 ‡	0.021 †	9.333	0.024	0.5810	0.0929	10.732	0.076	0.2531	0.0394 ¶	10.439	0.0308	0.3211	0.0358	10.713	0.0346	0.2776
M3P/M3(Ca+Mg) α_1	0.008 †	9.403	0.016	0.6552	0.0646	10.597	0.071	0.2715	0.0126 ¶	10.756	0.0114	0.5478	0.0133	11.000	0.0140	0.4924
OlsP/((2xP150)+OlsP)	0.0223	9.208	0.007	0.7393	0.4328	9.373	0.089	0.2026	0.0288	10.764	0.0030	0.7275	0.0491	10.809	0.0105	0.5284
M3P/((2xP150)+M3P)	0.0077	9.337	0.001	0.8807	0.2235	9.725	0.063	0.2859	0.0118	10.858	0.0010	0.8482	0.0232	10.942	0.0040	0.6967
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0049 †	9.729	0.001	0.9313	0.0947	10.704	0.060	0.297	0.0422 ¶	10.501	0.019	0.4301	0.047	10.627	0.027	0.3349
M3P/(M3(Ca+Mg) α_2 + M3P)	-0.0047 †	9.979	0.001	0.9205	0.0927	10.083	0.069	0.2622	0.0282 ¶	10.540	0.012	0.535	0.033	10.666	0.017	0.4451
*	significant at p< 0.05															
**	significant at p< 0.005															
***	significant at p< 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

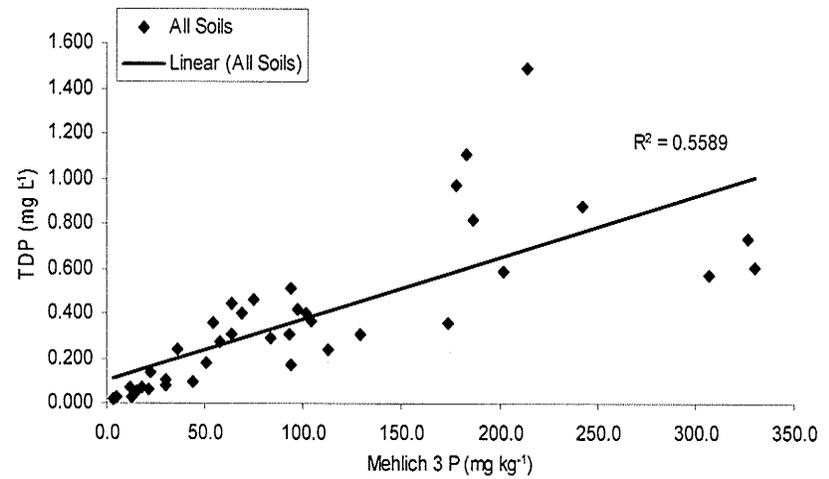
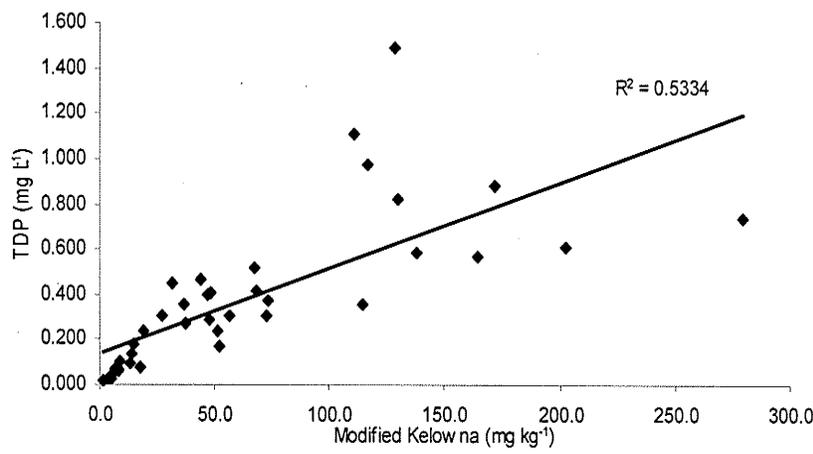
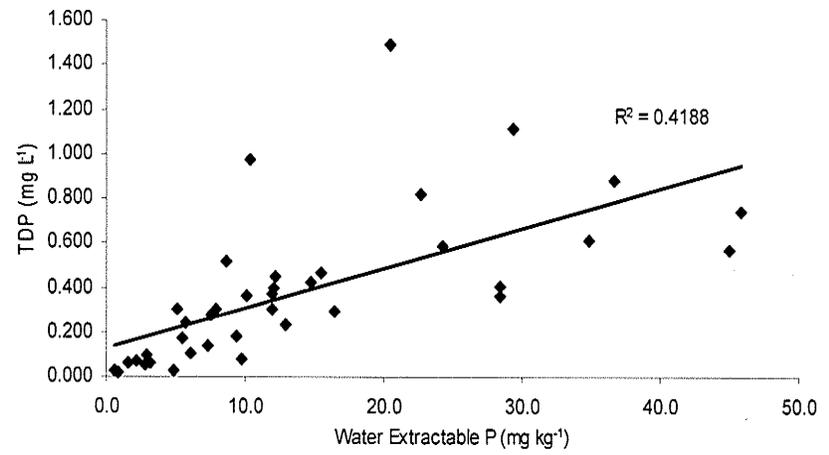
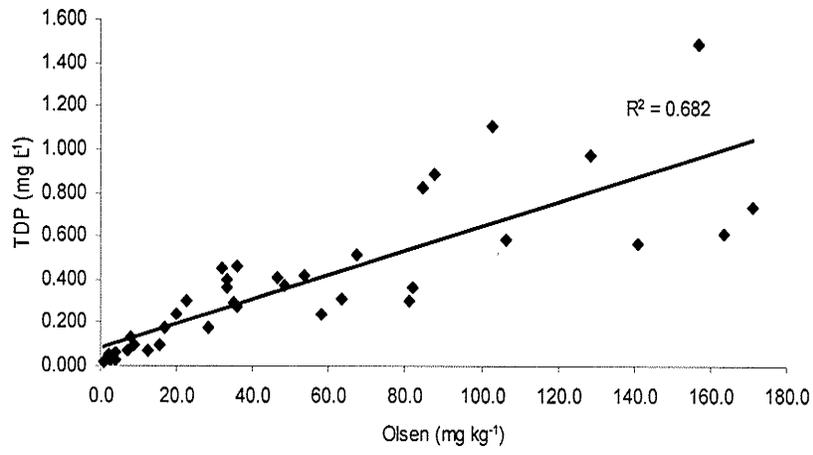


Fig VII.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TP) in 60-90 minutes of runoff.

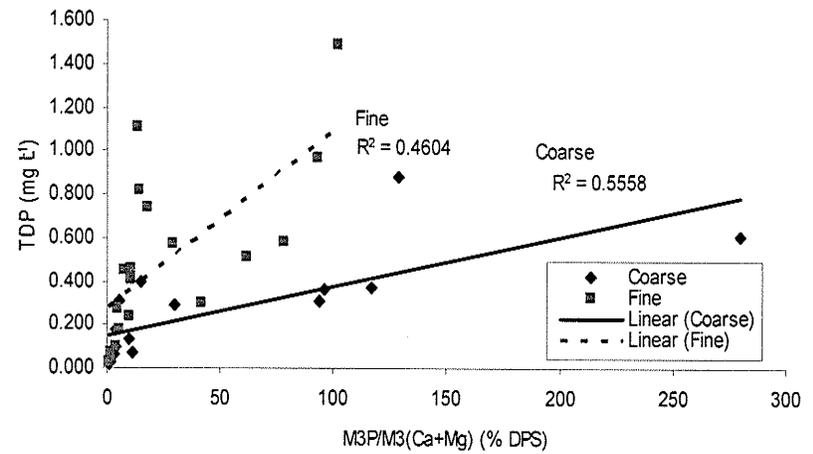
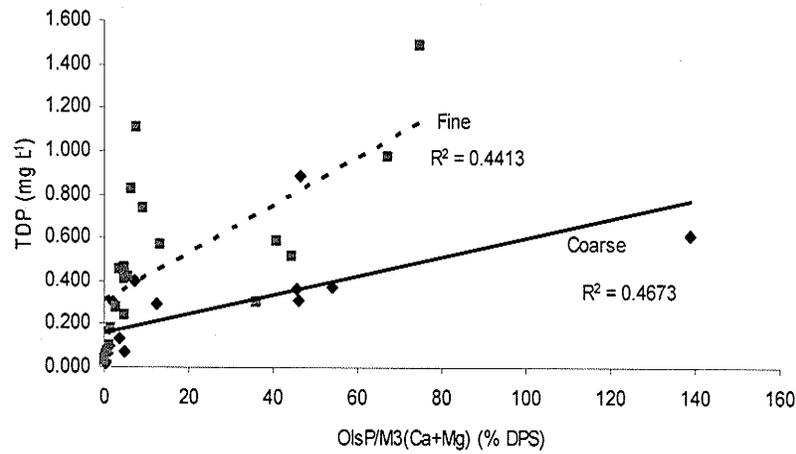
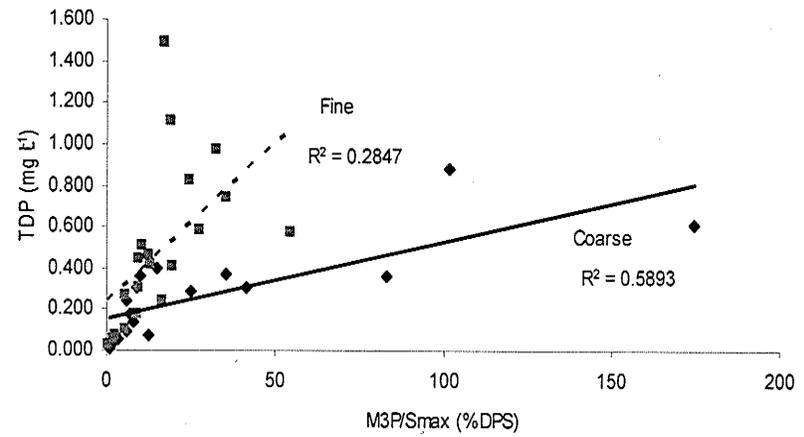
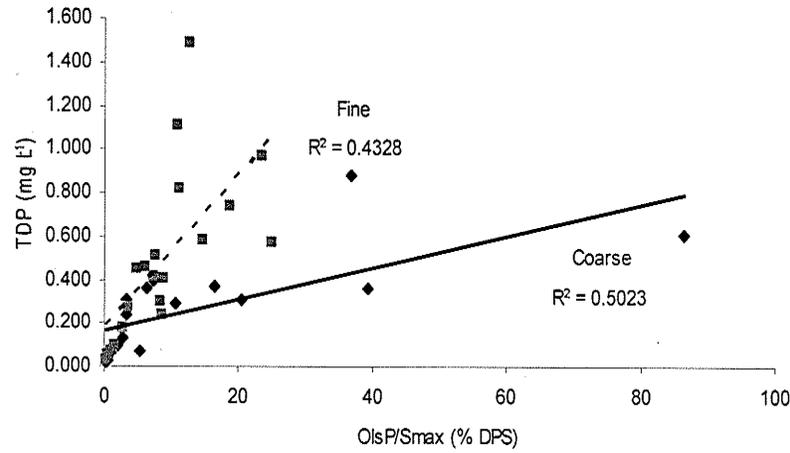


Fig VII.3: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

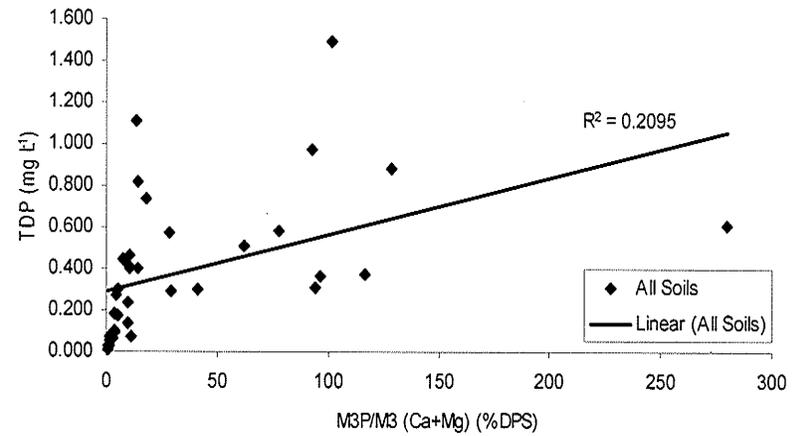
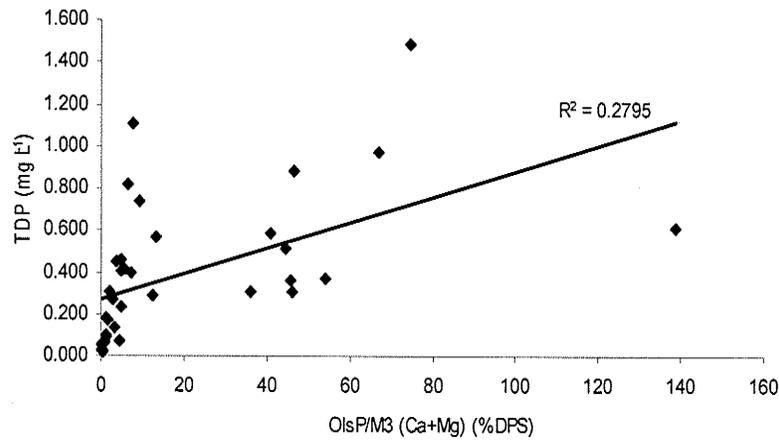
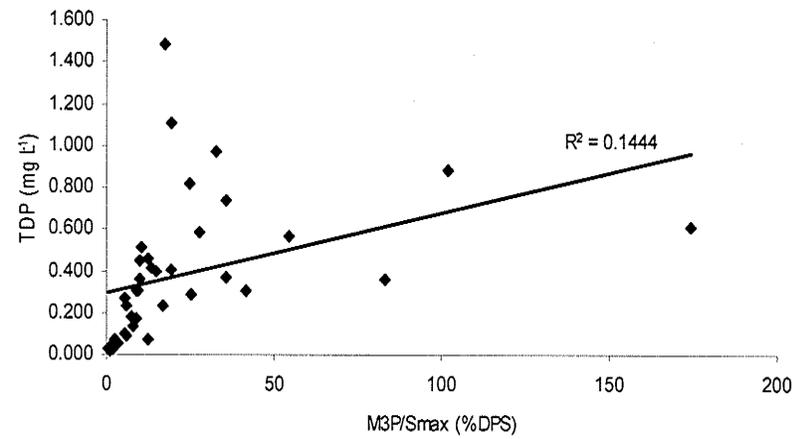
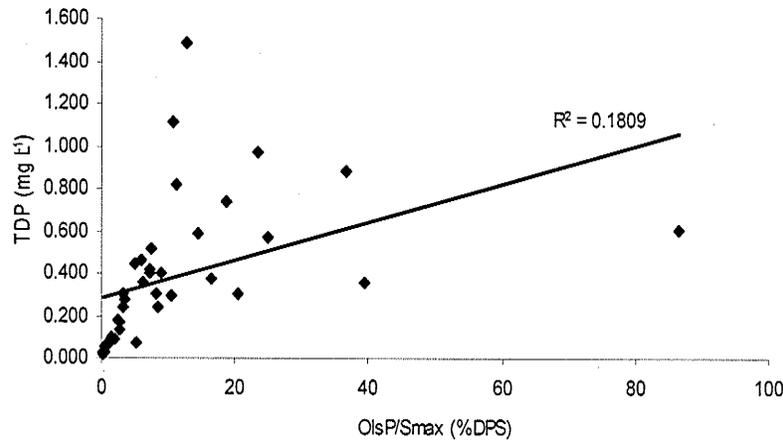


Fig VII.4: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

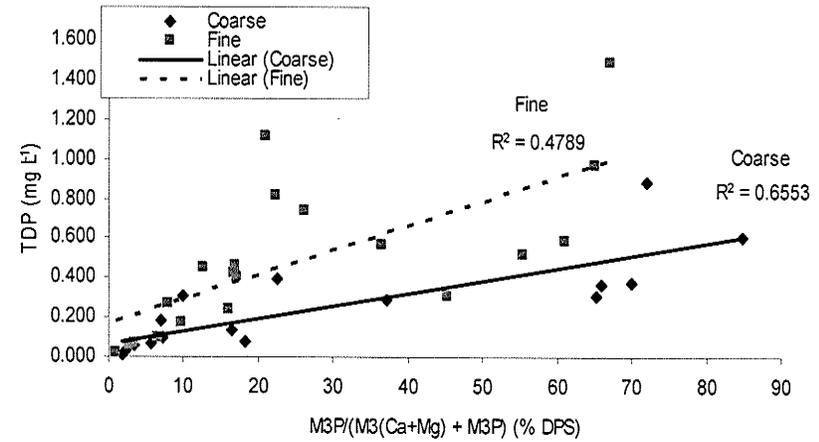
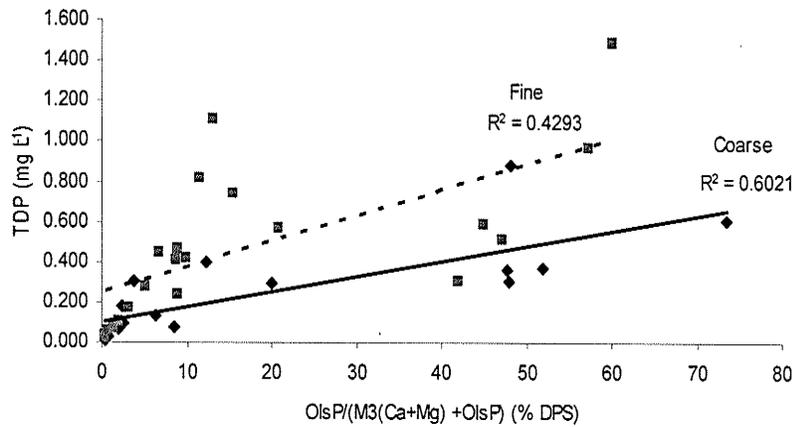
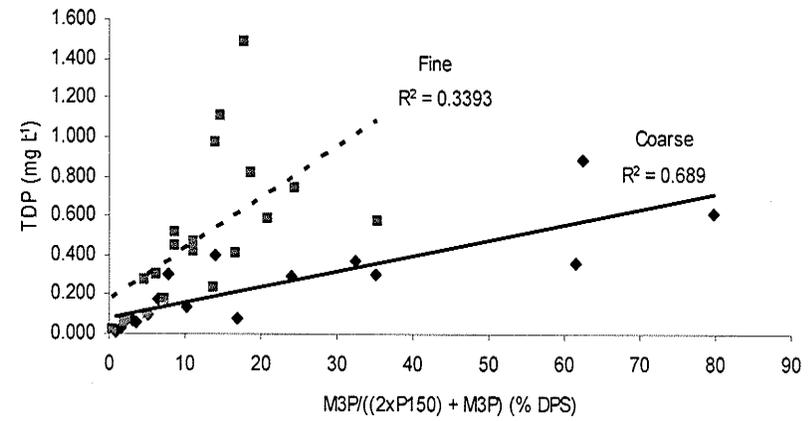
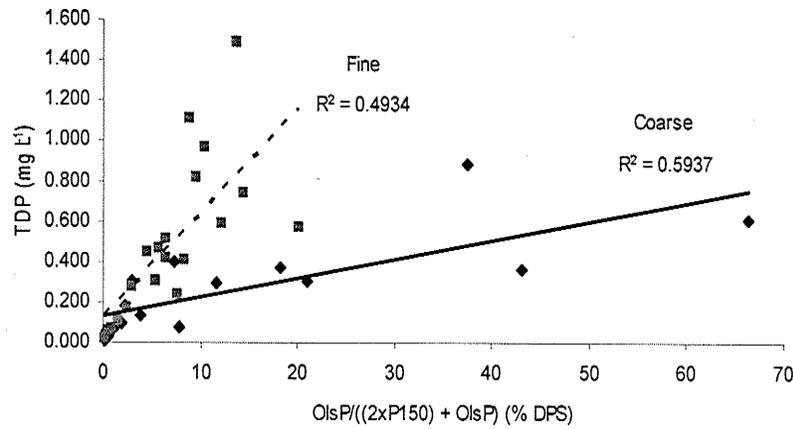


Fig VII.5: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

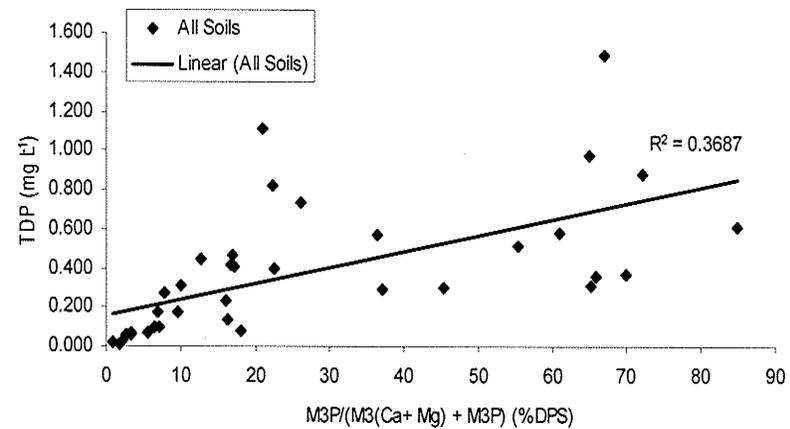
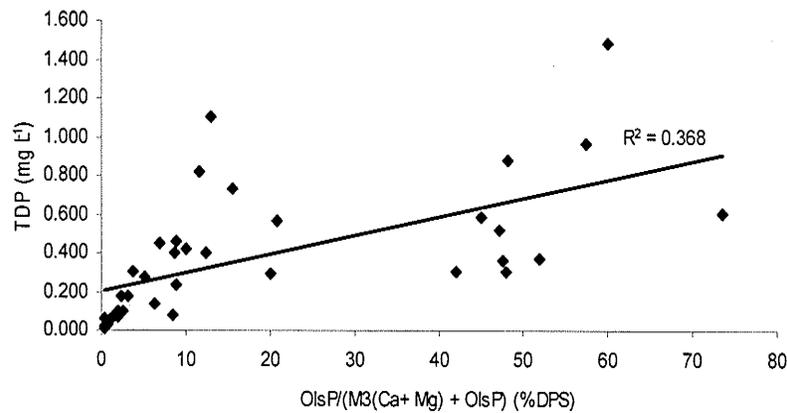
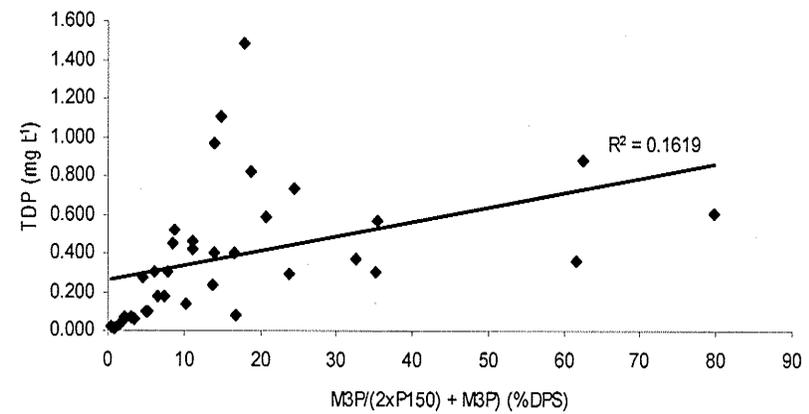
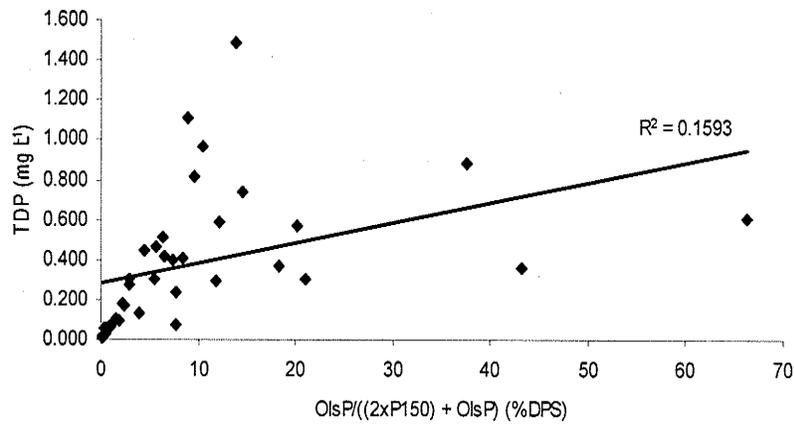


Fig VII.6: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

Table VII.1: Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 60-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0181 a	0.0510	0.79 ***	<0.0001	0.0157 a	0.2322	0.28 *	0.0156	0.0178	0.1300	0.42 ***	<0.0001	0.0318	0.0427	0.678 ***	<0.0001
Olsen (Ols-P)	0.0043 a†	0.1078	0.64 ***	<0.0001	0.0060 a	0.0820	0.67 ***	<0.0001	0.0056	0.0877	0.68 ***	<0.0001	0.0088	0.5643	0.726 ***	<0.0001
Modified Kelowna (MK-P)	0.0034 a	0.0964	0.78 ***	<0.0001	0.0037 a	0.2012	0.43 ***	0.0017	0.0038	0.1385	0.53 ***	<0.0001	0.0071	0.0251	0.614 ***	<0.0001
Mehlich 3 (M3-P)	0.0022 a	0.0847	0.73 ***	<0.0001	0.0029 a	0.1278	0.49 ***	0.0006	0.0027	0.0976	0.56 ***	<0.0001	0.0049	0.0599	0.503 ***	<0.0001
Ols-P/(P150)	0.0073 a	0.1653	0.50 ***	0.0010	0.0350 b	0.1774	0.43 **	0.0016	0.0090	0.2820	0.18 *	0.0078	0.0186	0.2840	0.171 *	0.0079
M3-P/(P150)	0.0037 a	0.1511	0.59 ***	0.0002	0.0153 b	0.2372	0.29 *	0.0154	0.0038	0.2942	0.15 *	0.0186	0.0057	0.3732	0.067	0.1064
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0045 a§	0.1424	0.51 **	0.0027	0.0105 b	0.3288	0.43 **	0.0025	0.0059 ¶	0.2763	0.27 **	0.0015	0.0141	0.2089	0.432 ***	<0.0001
M3-P/M3(Ca+Mg)α ₁	0.0024 a§	0.1253	0.61 ***	0.0006	0.0078 b	0.3024	0.44 **	0.0019	0.0027 ¶	0.2941	0.20 **	0.0077	0.0059	0.2932	0.223 **	0.0036
Ols-P/((2xP150)+Ols-P)	0.0091 a	0.1463	0.56 ***	0.0004	0.0510 b	0.1251	0.49 ***	0.0006	0.0101	0.2816	0.16 *	0.0121	0.0240	0.2485	0.210 **	0.003
M3-P/((2xP150)+M3-P)	0.0074 a	0.1077	0.64 ***	<0.0001	0.0259 b	0.1719	0.34 *	0.0070	0.0075	0.2580	0.16 *	0.0113	0.0150	0.2538	0.139 *	0.0212
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0075 a§	0.1058	0.60 ***	0.0004	0.0126 a	0.2551	0.43 **	0.0017	0.0095 ¶	0.2015	0.37 ***	<0.0001	0.0190	0.1230	0.346 ***	0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0063 a§	0.0664	0.66 ***	0.0001	0.0122 a	0.1772	0.48 ***	0.0007	0.0081 ¶	0.1613	0.37 ***	<0.0001	0.0150	0.0888	0.275 ***	0.0007
Ols-P/(PSI+Ols-P) ††	0.0063 a‡‡	0.1162	0.72 ***	<0.0001	0.025 b	0.1083	0.50 ***	0.0005	0.0075 §§	0.2417	0.25 **	0.0017	0.0127	0.2625	0.151 **	0.0145
WEP/(PSI+WEP) ††	0.0086 ‡‡	0.1410	0.77 ***	<0.0001	0.0331	0.3307	0.14	0.1036	0.0070 §§	0.3209	0.11 *	0.0411	0.0217	0.2564	0.378 ***	<0.0001
MK-P/(PSI+MK-P) ††	0.006 a‡‡	0.1072	0.71 ***	<0.0001	0.0189 b	0.1722	0.39 **	0.0033	0.0069 §§	0.2402	0.23 **	0.0025	0.0162	0.1301	0.349 ***	<0.0001
M3-P/(PSI+M3-P) ††	0.006 a‡‡	0.0700	0.70 ***	<0.0001	0.016 b	0.1072	0.40 **	0.0028	0.0072 §§	0.1867	0.26 **	0.0012	0.0155	0.0462	0.318 ***	0.0002

*, **, *** significance at p<0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Appendix VIII: STP and DPS regressions with PP for 60- 90 minute interval

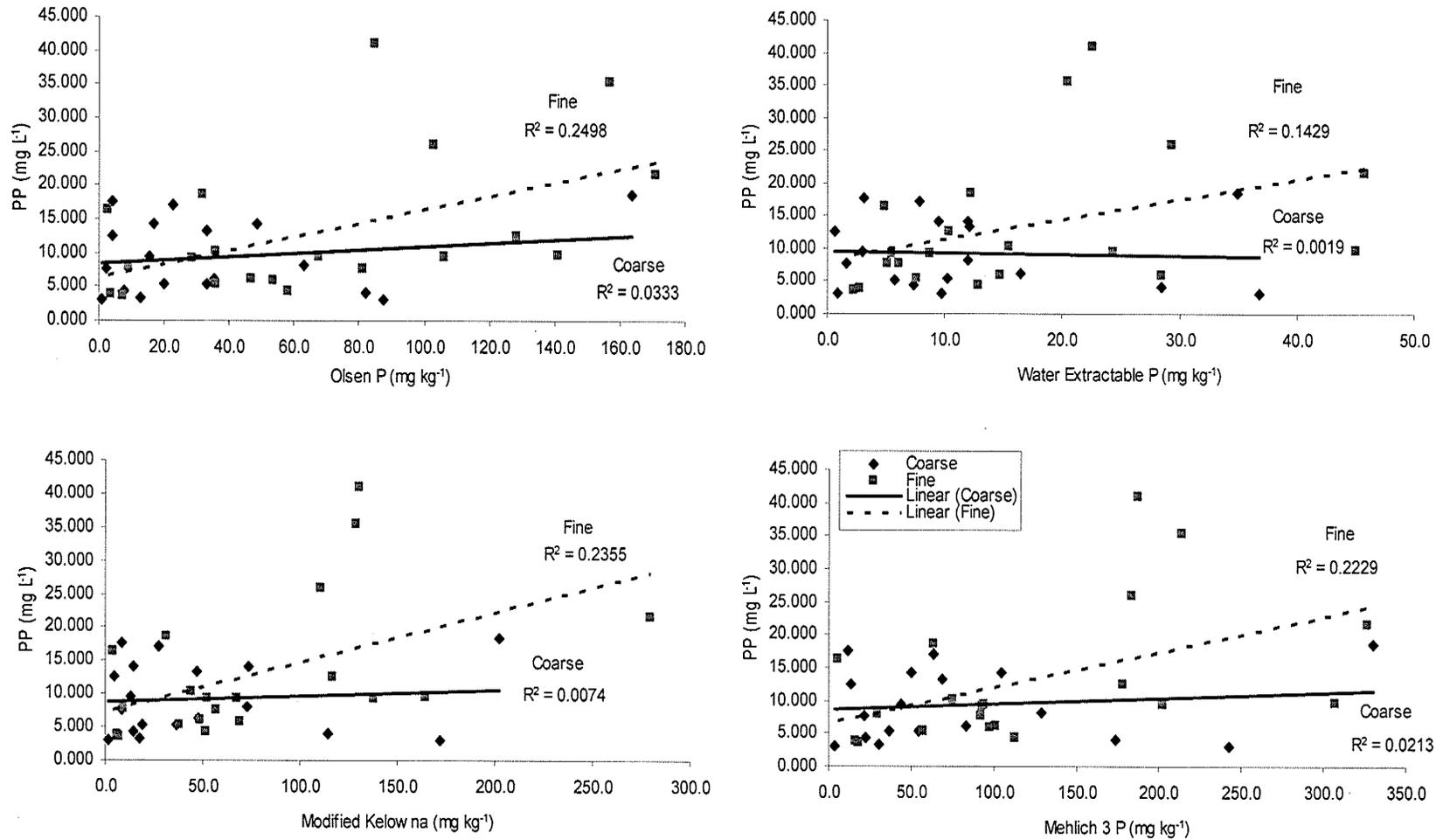


Fig VIII.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 60-90 minutes of runoff.

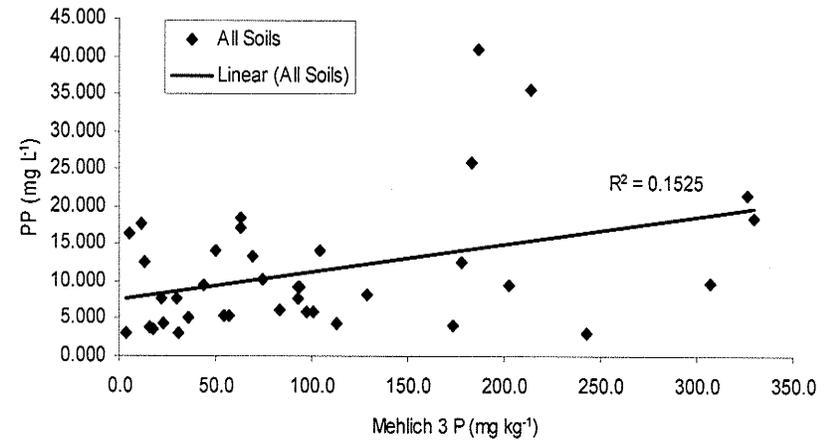
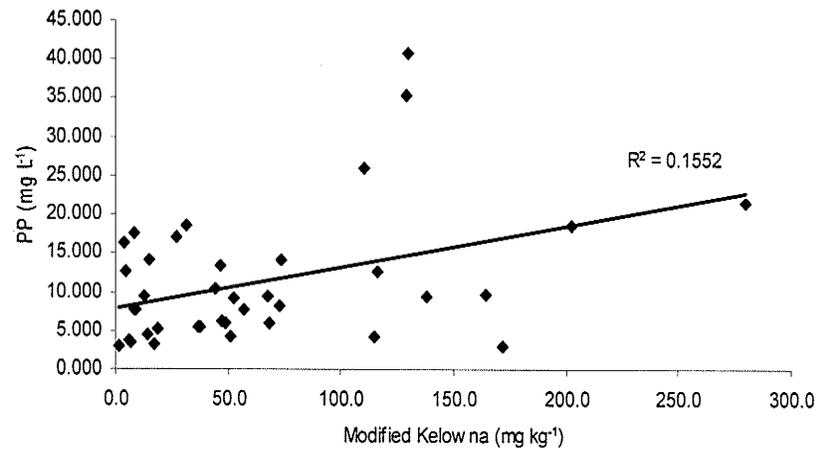
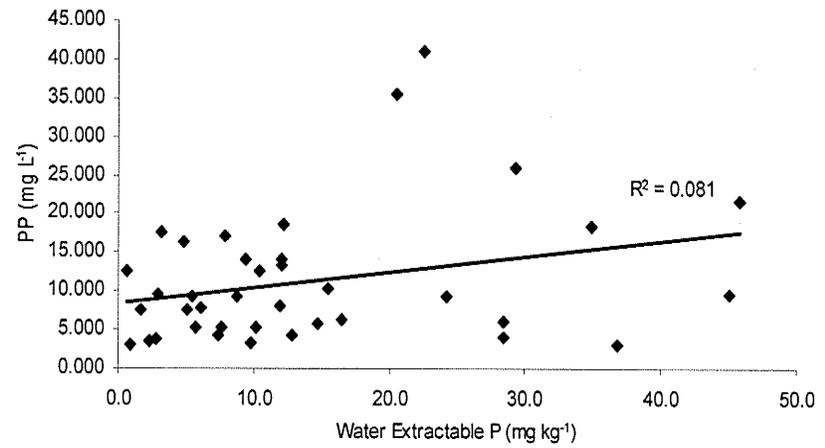
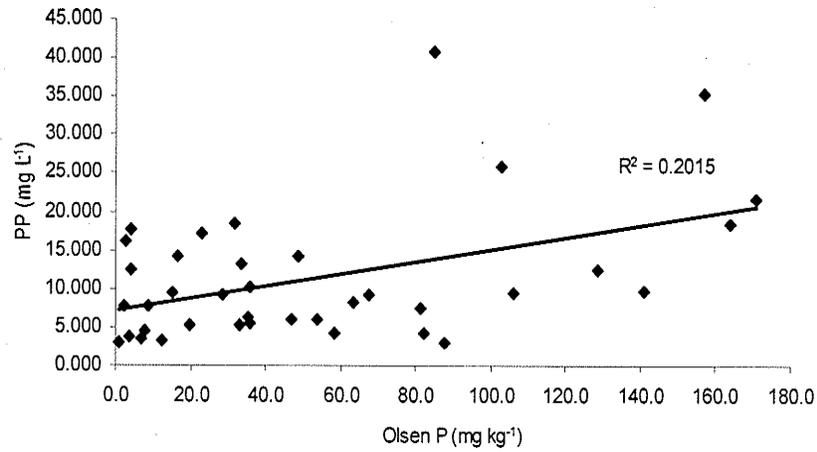


Fig VIII.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 60-90 minutes of runoff.

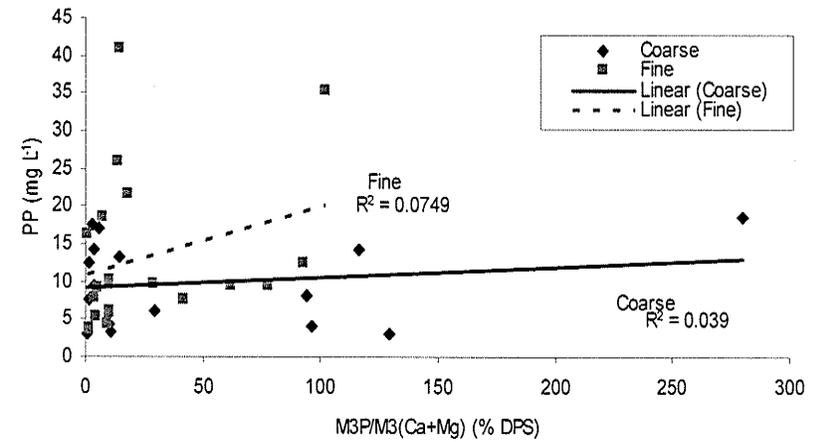
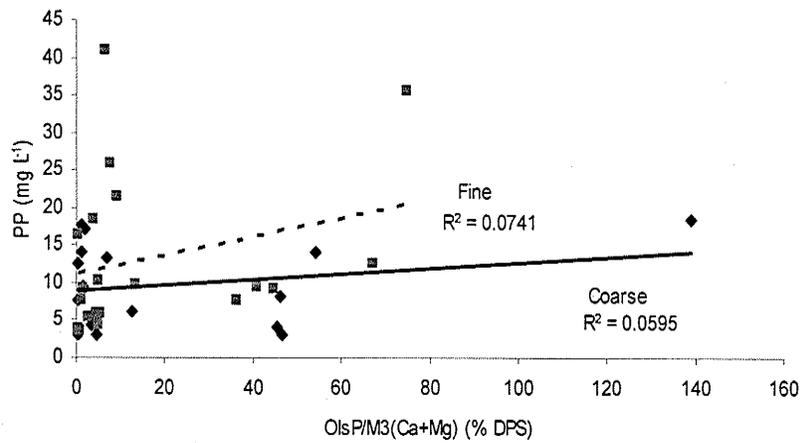
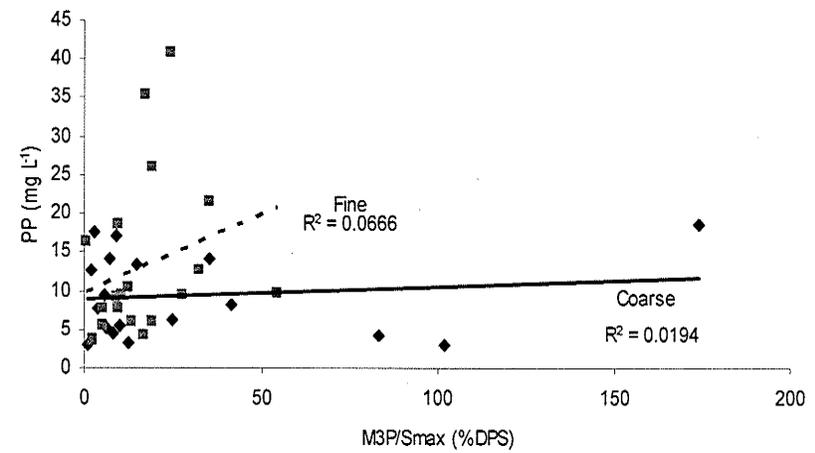
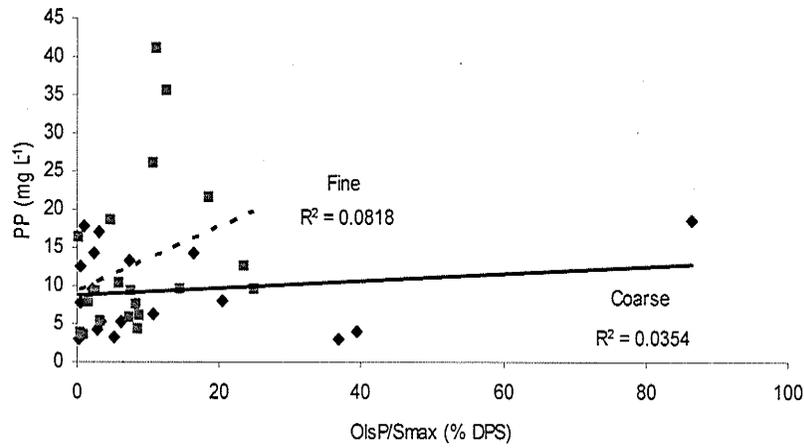


Fig VIII.3: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

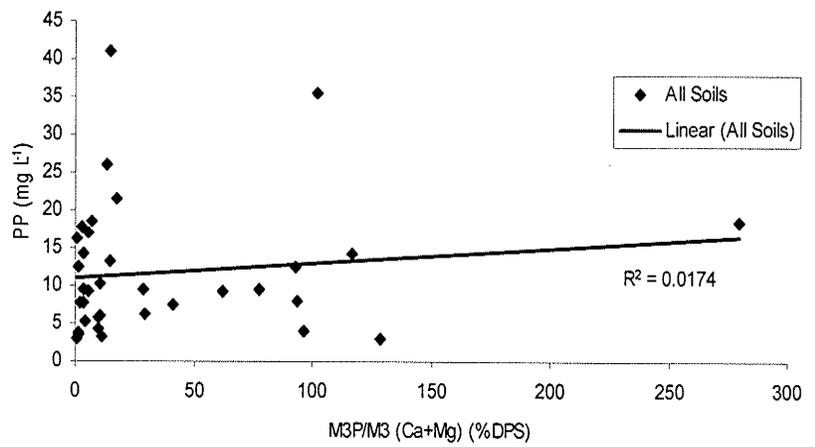
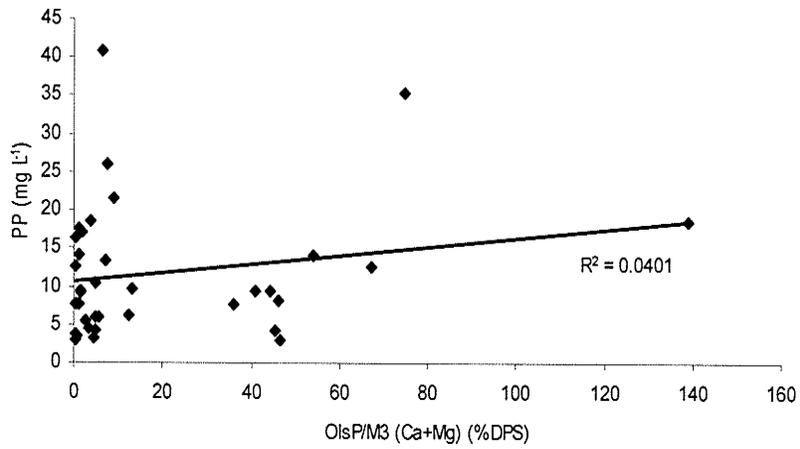
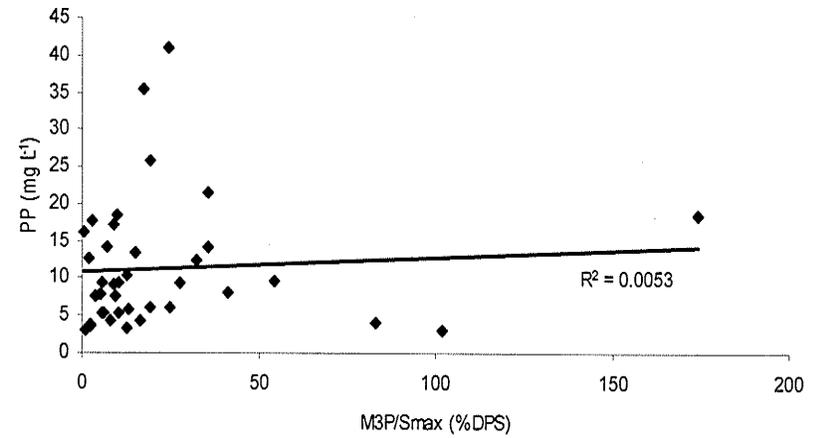
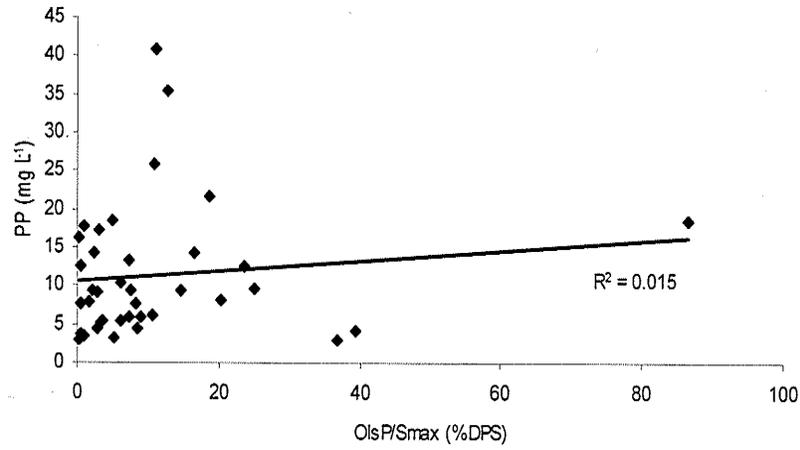


Fig VIII.4: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

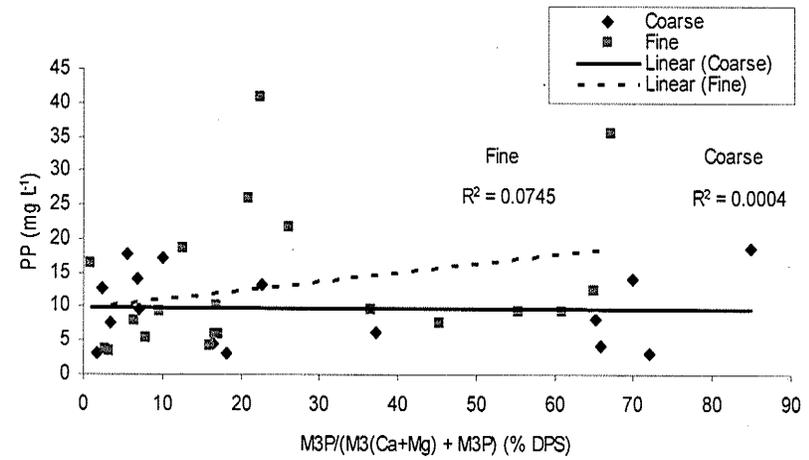
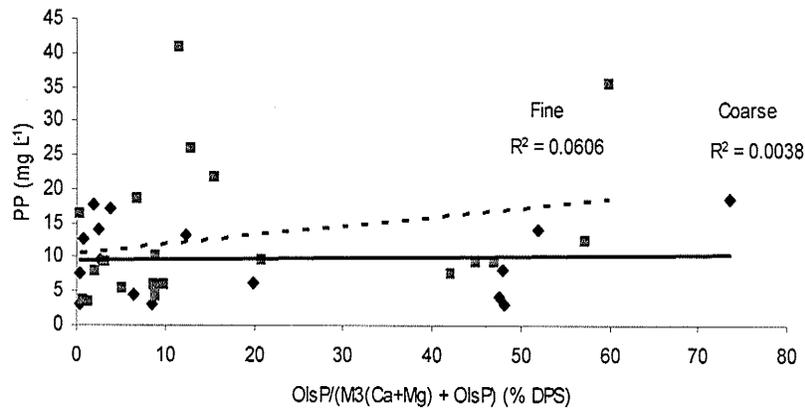
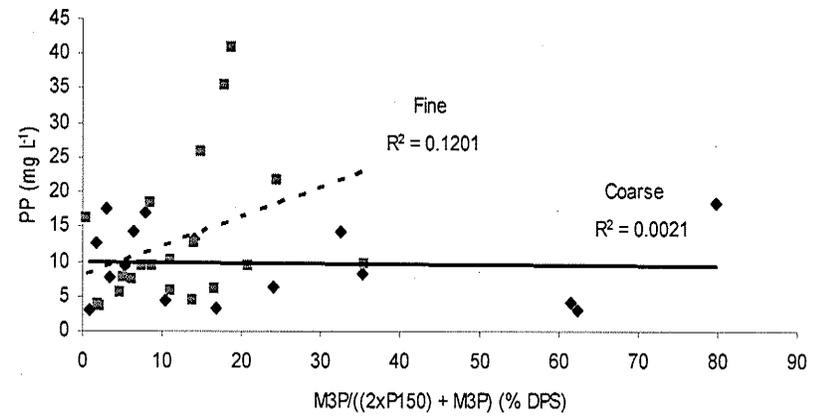
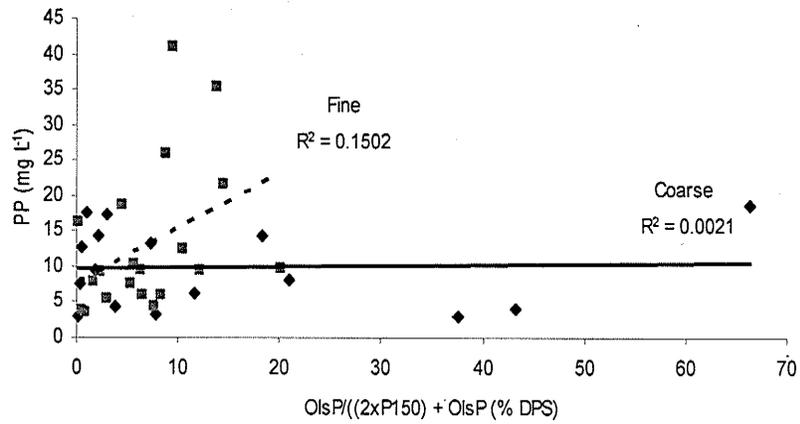


Fig VIII.5: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

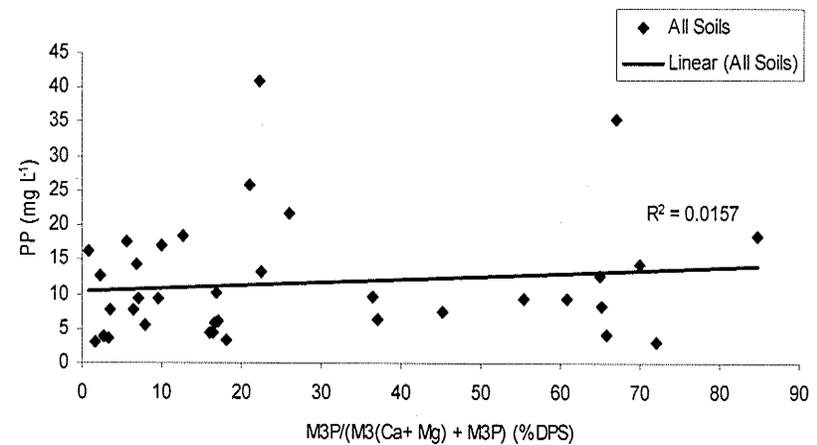
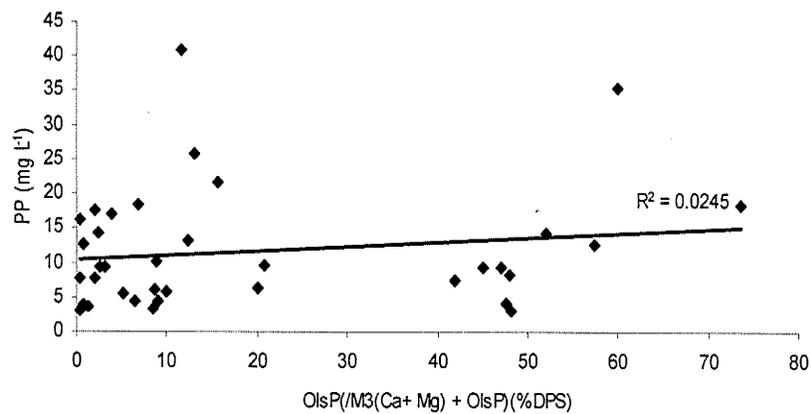
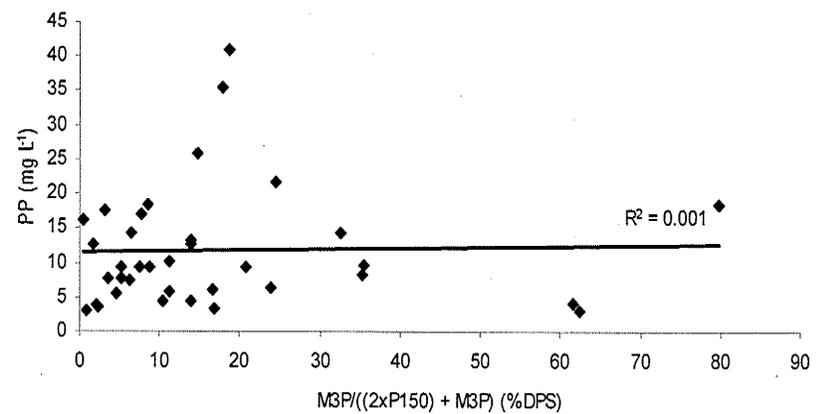
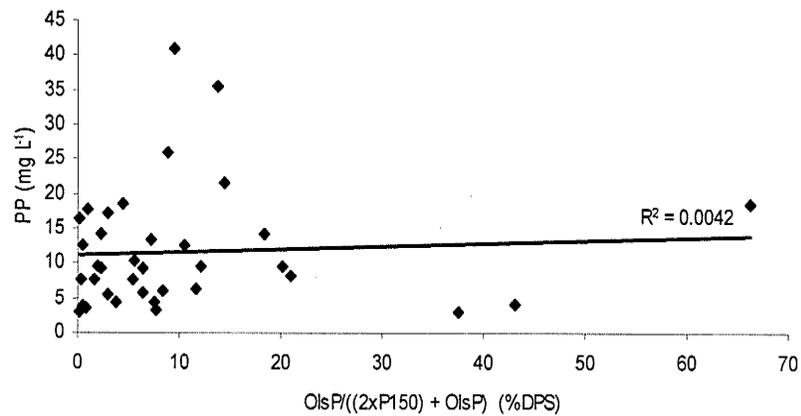


Fig VIII.6: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

Table VIII.1: Linear regression for concentration of particulate P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 60-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	-0.0214	9.532	0.002	0.8652	0.3055	8.188	0.143	0.1003	0.2021	8.461	0.0811	0.0832	0.122	9.476	0.0679	0.1044
Olsen (OlsP)	0.0240	8.409	0.033	0.4688	0.1002	6.369	0.250 *	0.0248	0.0781	7.192	0.201 **	0.0047	0.048	8.534	0.145 *	0.0154
Modified Kelowna (MKP)	0.0080	8.882	0.007	0.7343	0.0748	7.350	0.236 *	0.0301	0.0526	7.931	0.155 *	0.0144	0.039	8.681	0.124 *	0.0257
Mehlich 3 (M3P)	0.0091	8.533	0.021	0.5638	0.0540	6.526	0.223 *	0.0356	0.0369	7.487	0.153 *	0.0153	0.032	7.842	0.149 *	0.0139
OlsP/(P150)	0.0471	8.640	0.035	0.4545	0.4166	9.457	0.082	0.2215	0.6670	10.575	0.015	0.4638	0.078	10.651	0.020	0.3802
M3P/(P150)	0.0165	8.780	0.019	0.5815	0.2022	9.836	0.067	0.2721	0.0189	10.883	0.005	0.6642	0.022	11.066	0.007	0.6133
OlsP/M3(Ca+Mg) α_1 †	0.0401 †	8.588	0.072	0.3330	0.1330	10.675	0.083	0.2306	0.0634 ¶	10.182	0.047	0.2204	0.033	10.989	0.017	0.4531
M3P/M3(Ca+Mg) α_1	0.0161 †	8.702	0.050	0.4242	0.0973	10.352	0.086	0.2240	0.0225 ¶	10.606	0.021	0.4096	0.014	11.178	0.009	0.5844
OlsP/((2xP150)+OlsP)	0.0265	8.934	0.725	0.7252	0.7704	7.675	0.150	0.0914	0.0517	10.802	0.006	0.6327	0.053	11.012	0.007	0.6073
M3P/((2xP150)+M3P)	0.0027	9.222	0.000	0.9623	0.4219	8.009	0.120	0.1345	0.0245	10.912	0.003	0.7596	0.026	11.136	0.003	0.7397
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0176 †	9.175	0.006	0.7823	0.1298	10.757	0.061	0.2955	0.0637 ¶	10.357	0.025	0.3627	0.048	10.878	0.015	0.468
M3P/(M3(Ca+Mg) α_2 + M3P)	-0.0017 †	9.598	0.000	0.9744	0.1315	9.796	0.075	0.2442	0.0432 ¶	10.400	0.016	0.4682	0.033	10.909	0.010	0.5616
*	significant at p< 0.05															
**	significant at p< 0.005															
***	significant at p< 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix IX: STP and DPS regressions with TP for 60- 90 minute interval

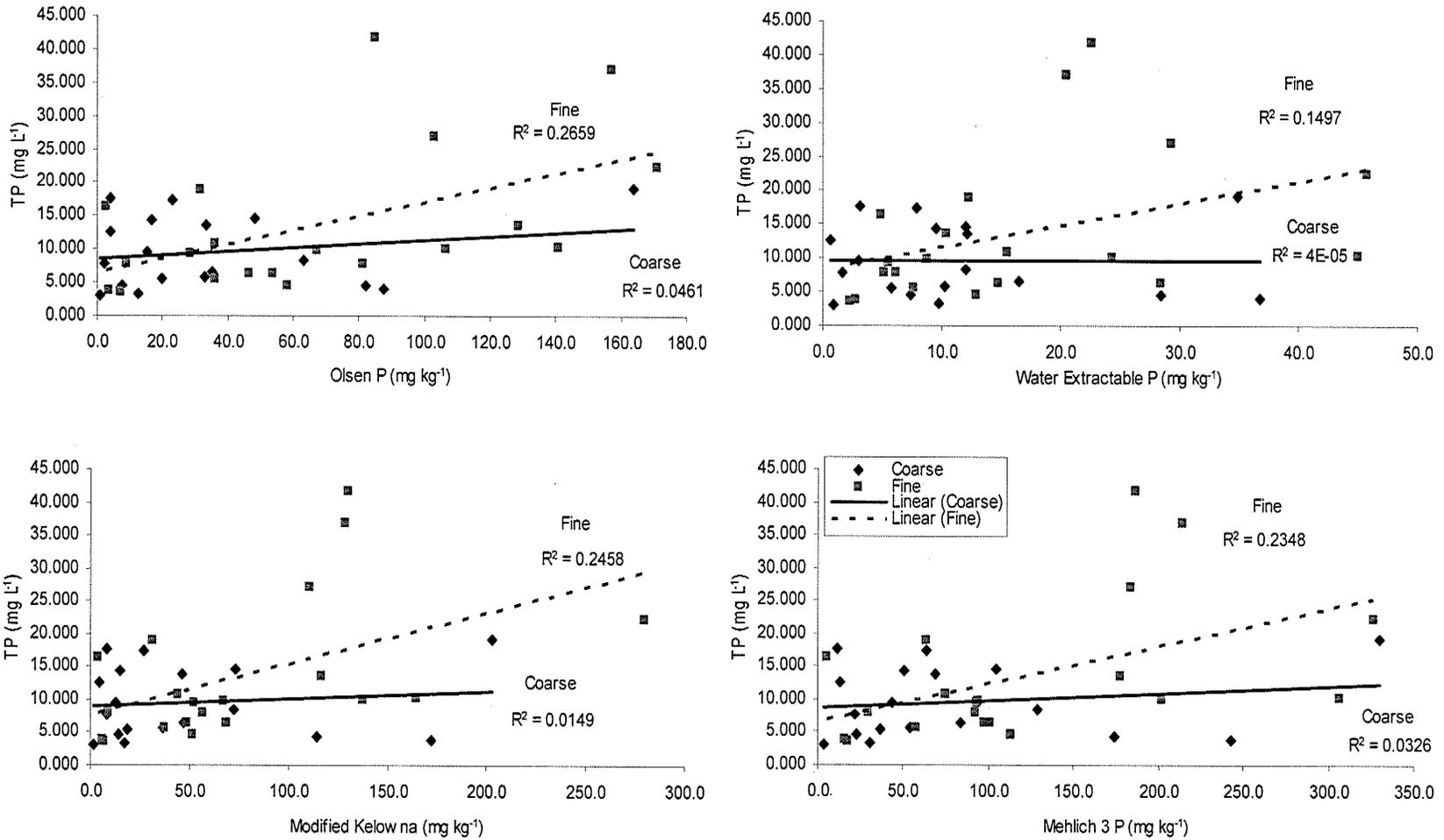


Fig IX.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 60-90 minutes of runoff.

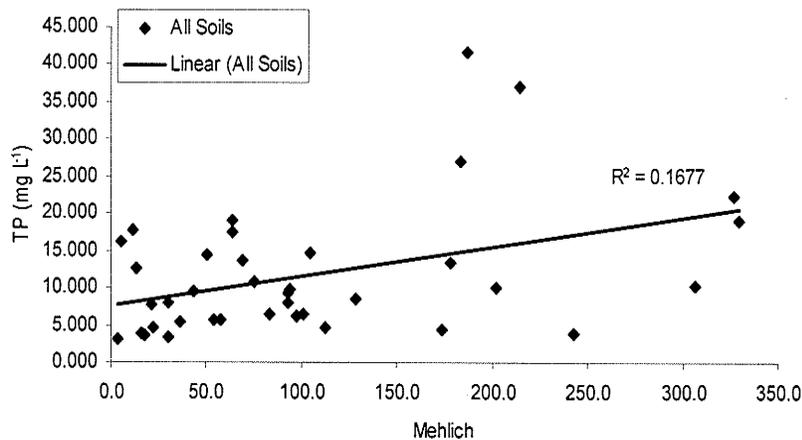
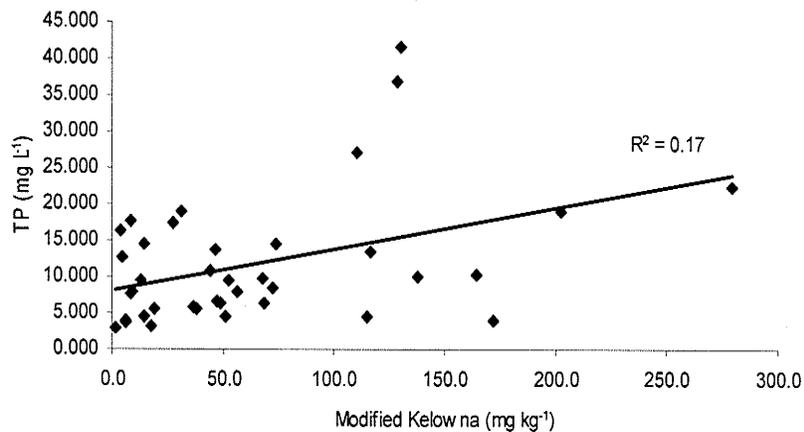
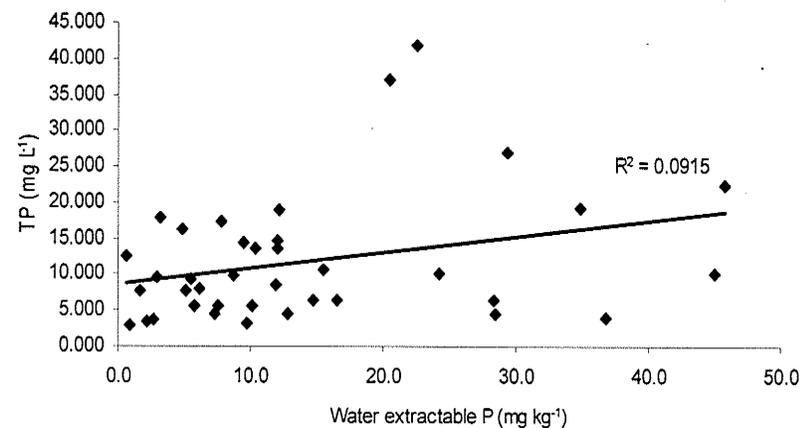
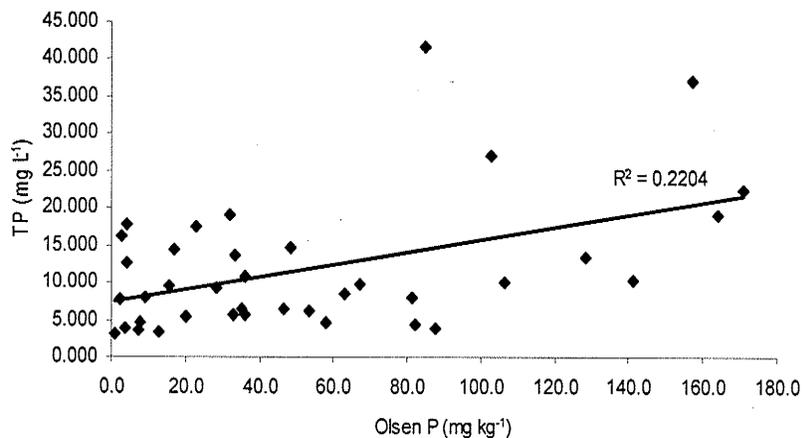


Fig IX.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 60-90 minutes of runoff.

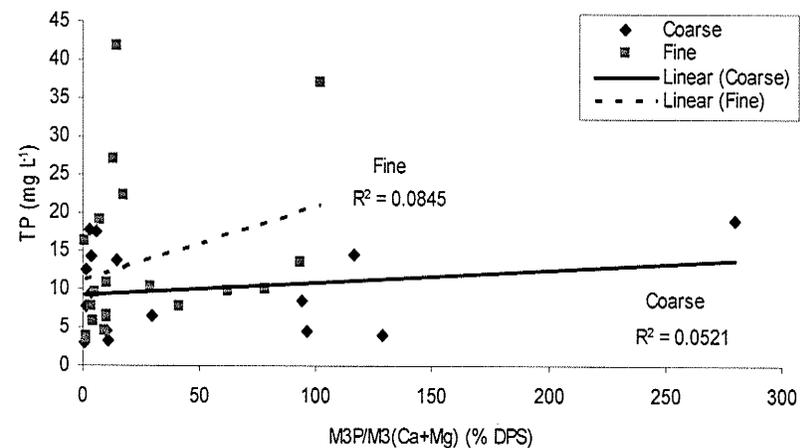
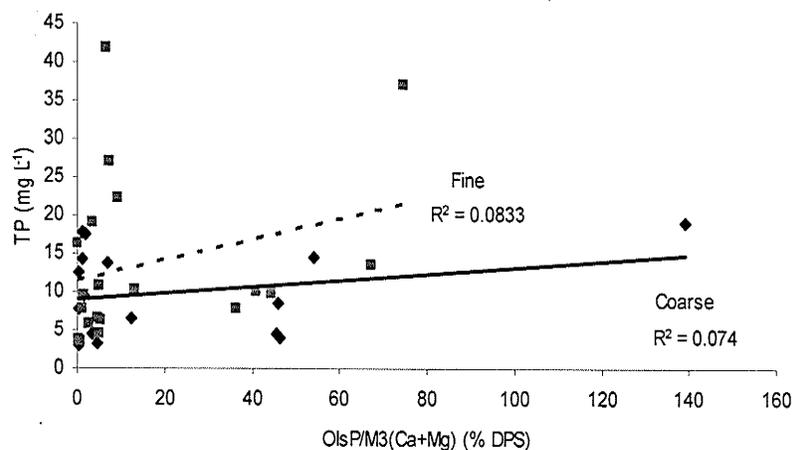
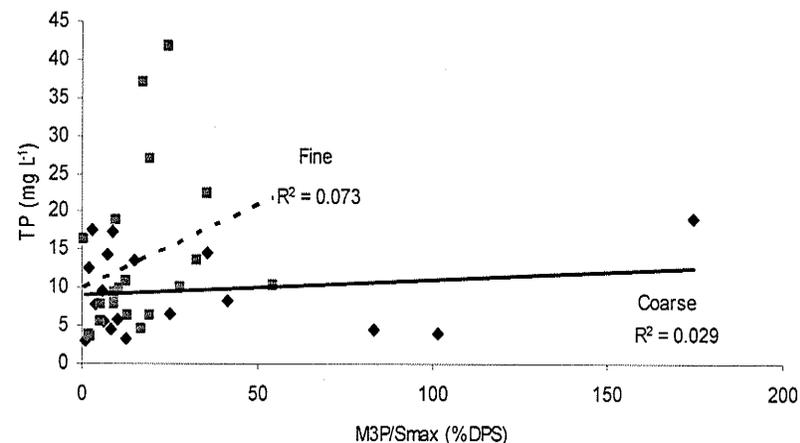
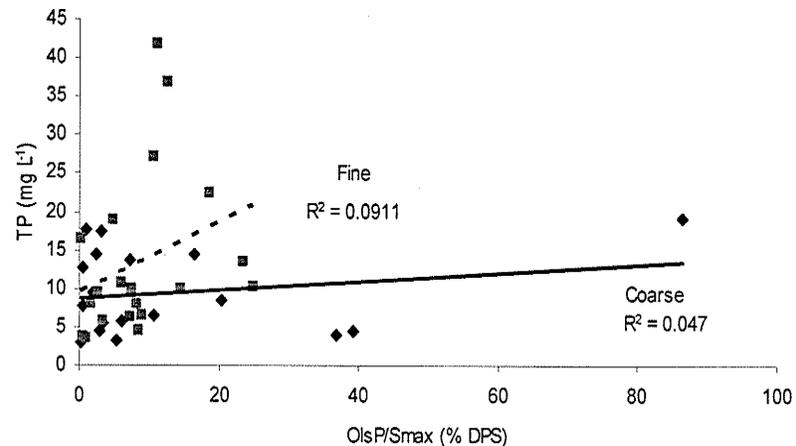


Fig IX.3: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

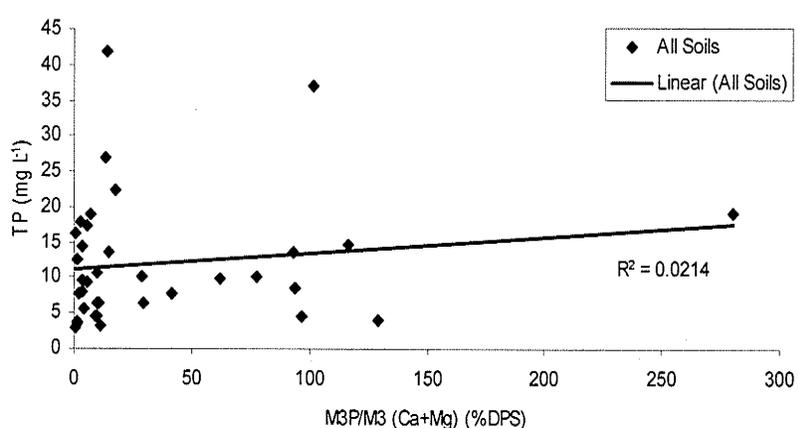
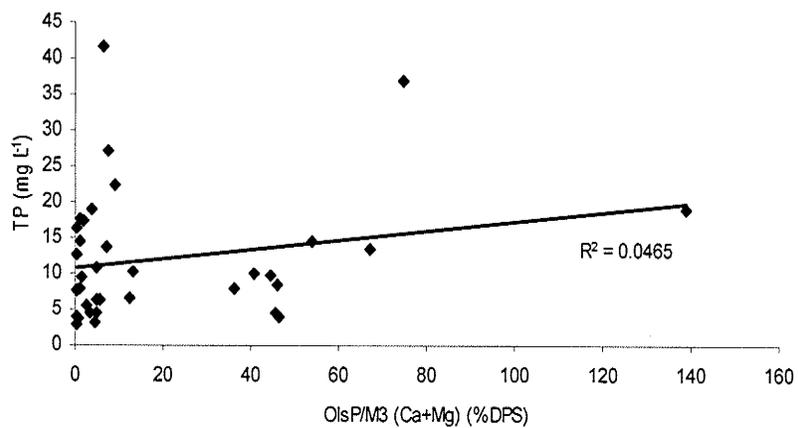
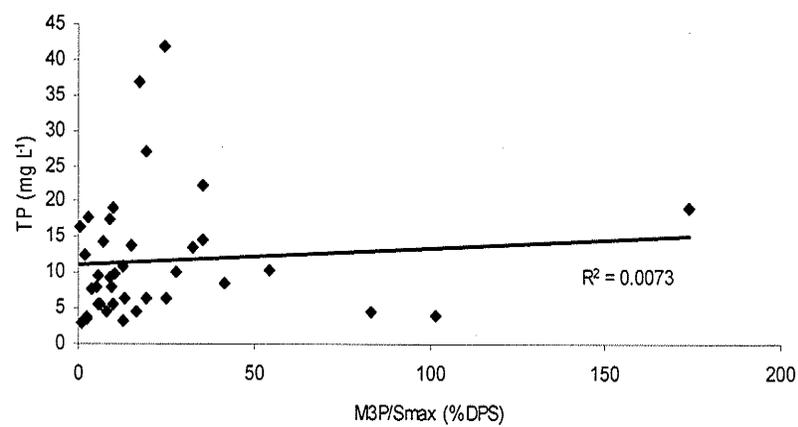
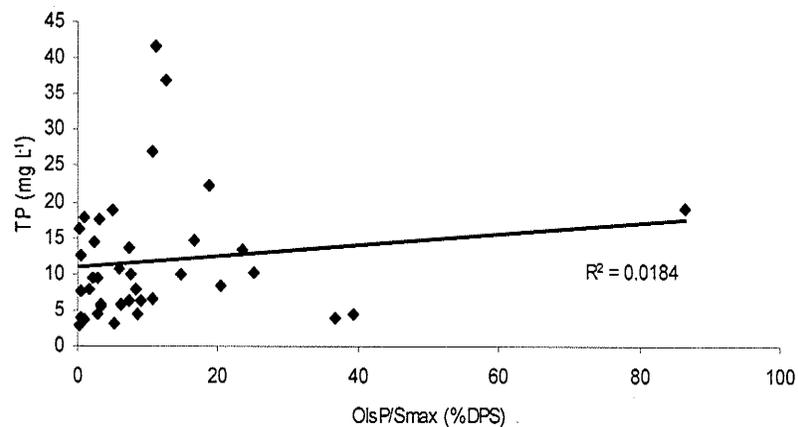


Fig IX.4: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 60-90 minutes of runoff (Ige et al., 2005a).

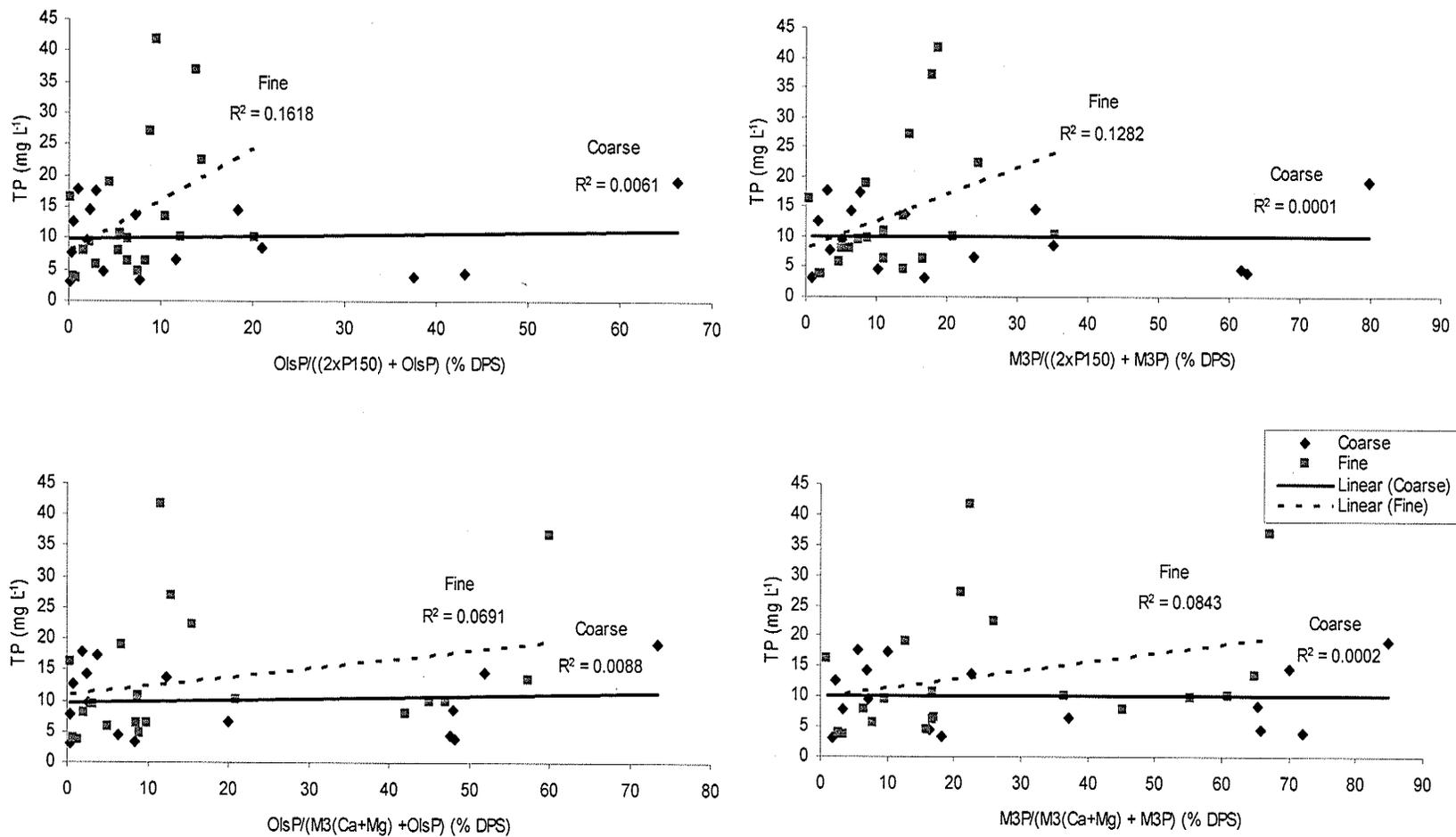


Fig IX.5: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

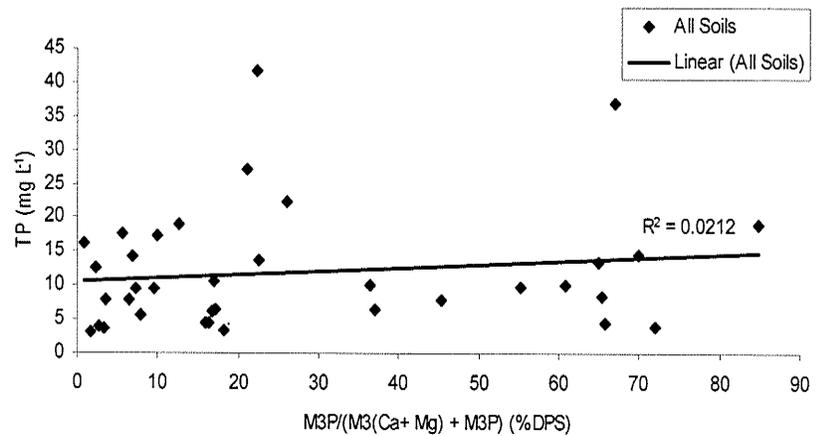
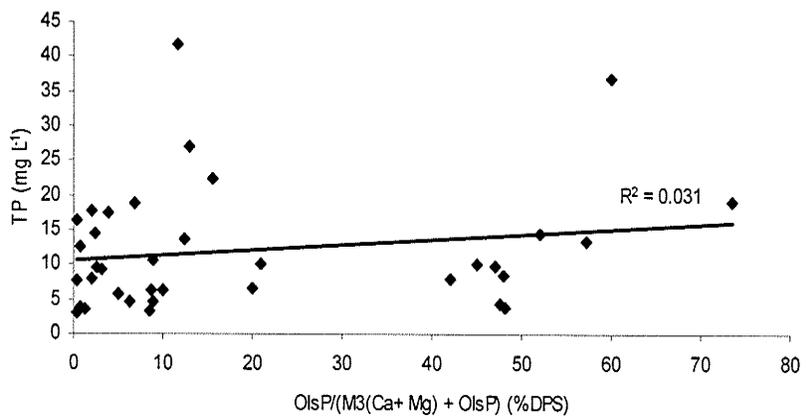
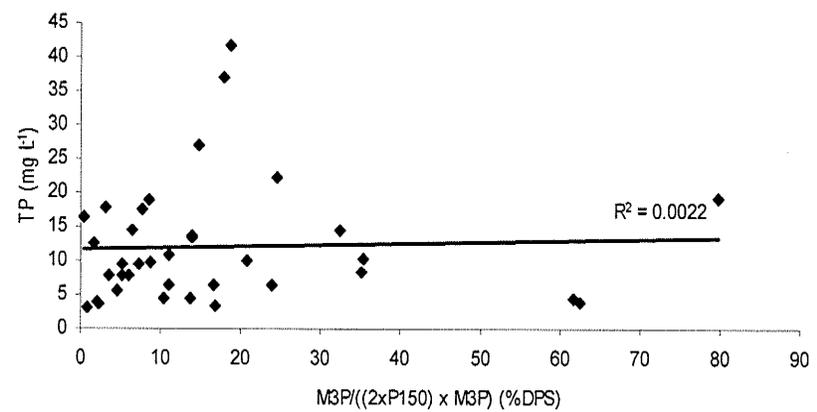
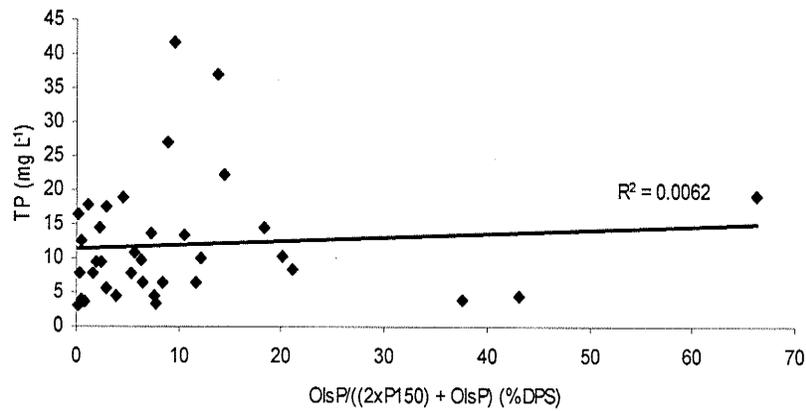


Fig IX.6 : Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 60-90 minutes of runoff (Akinremi et al., 2007).

Table IX.1: Linear regression for concentration of total P (TP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 60-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0286	9.165	0.004	0.7991	0.1608	9.837	0.074	0.2461	0.1284	9.238	0.056	0.1530	0.1023	9.565	0.085	0.0683
Olsen (OlsP)	0.0219	8.706	0.035	0.458	0.0683	7.831	0.217 *	0.0387	0.0560	8.095	0.177 *	0.0085	0.0396	8.805	0.176 *	0.007
Modified Kelowna (MKP)	0.0088	9.064	0.011	0.6756	0.0540	8.259	0.230 *	0.0325	0.0394	8.517	0.149 *	0.0167	0.0336	8.820	0.165 *	0.0093
Mehlich 3 (M3P)	0.0104	8.642	0.0350	0.4546	0.0353	8.120	0.178	0.0640	0.0266	8.297	0.135 *	0.0233	0.0256	8.373	0.165 *	0.0092
OlsP/(P150)	0.0544	8.804	0.047	0.3876	0.4516	9.634	0.091	0.196	0.0757	10.857	0.0184	0.4167	0.0962	10.935	0.0300	0.2876
M3P/(P150)	0.0203	8.931	0.029	0.4992	0.2170	10.073	0.073	0.2494	0.0226	11.177	0.0072	0.6101	0.0277	11.439	0.0102	0.5345
OlsP/M3(Ca+Mg) α_1 †	0.0447 †	8.730	0.089	0.2801	0.1434	11.004	0.092	0.2071	0.0694 ¶	10.459	0.053	0.1904	0.0472	11.198	0.0321	0.2958
M3P/M3(Ca+Mg) α_1	0.0185 †	8.827	0.065	0.3578	0.1051	10.654	0.094	0.2005	0.0252 ¶	10.900	0.0254	0.3677	0.0201	11.471	0.017	0.449
OlsP/((2xP150)+OlsP)	0.0355	9.080	0.0142	0.637	0.8214	7.800	0.162	0.0787	0.062	11.084	0.009	0.5770	0.077	11.26	0.014	0.4662
M3P/((2xP150)+M3P)	0.0101	9.330	0.002	0.8606	0.4478	8.181	0.128	0.1212	0.0321	11.170	0.004	0.6962	0.0414	11.384	0.007	0.6094
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0253 †	9.263	0.012	0.6917	0.1424	11.012	0.069	0.2627	0.0733 ¶	10.556	0.0317	0.306	0.0665	11.000	0.028	0.3204
M3P/(M3(Ca+Mg) α_2 + M3P)	0.0048 †	9.649	0.0007	9264	0.1437	9.973	0.0843	0.2143	0.0512 ¶	10.559	0.0216	0.3996	0.0481	10.999	0.0193	0.4124
*	significant at p< 0.05															
**	significant at p< 0.005															
***	significant at p< 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix X: STP and DPS regressions with TDP for 0- 90 minute interval

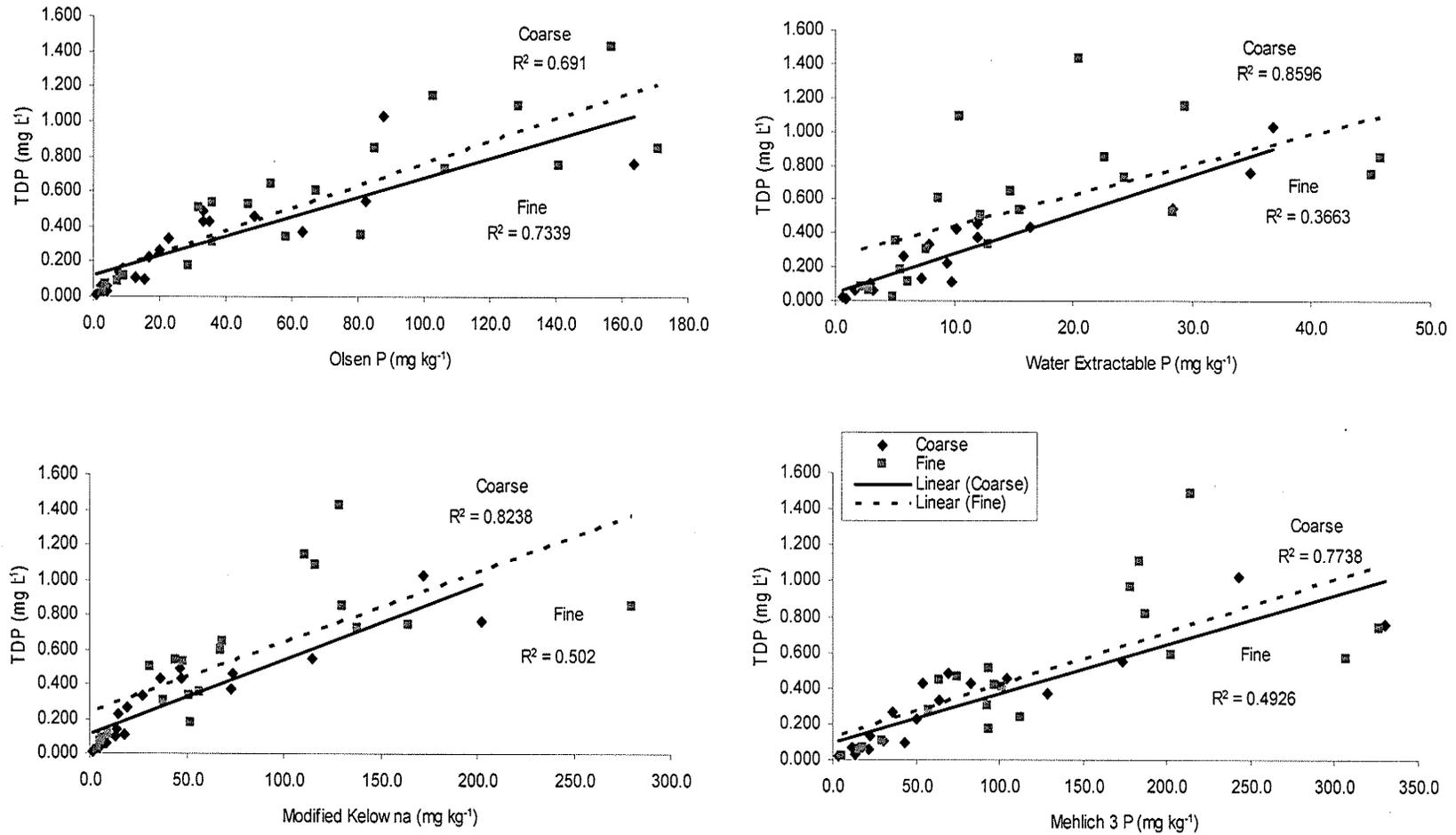


Fig X.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in 0-90 minutes of runoff.

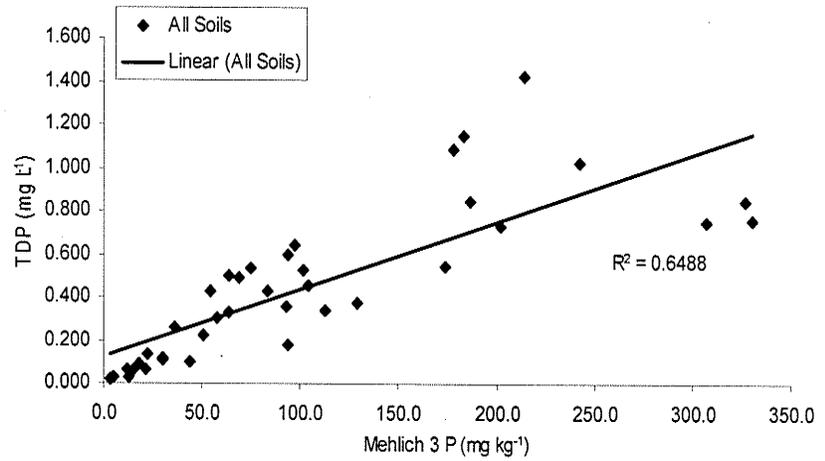
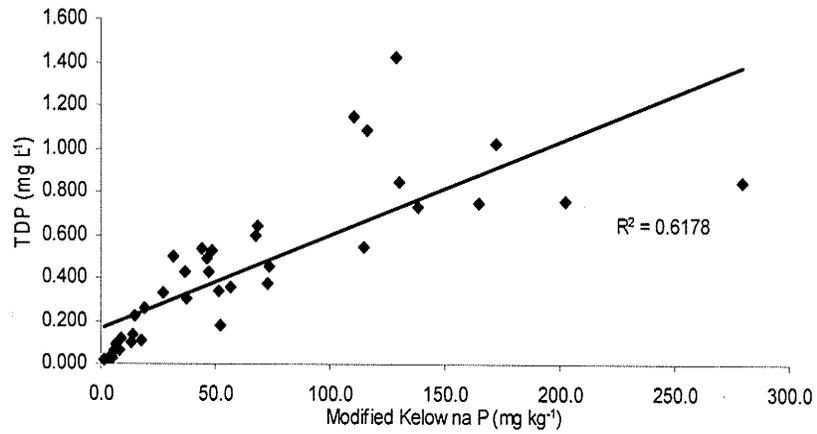
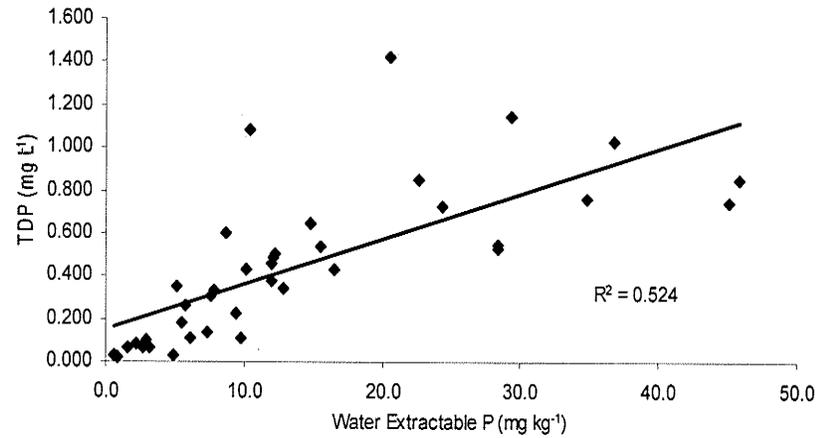
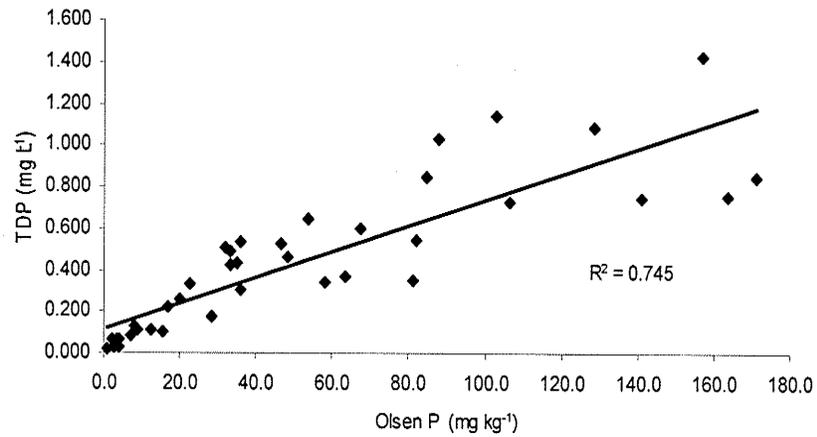


Fig X.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total dissolved P (TDP) in 0-90 minutes of runoff.

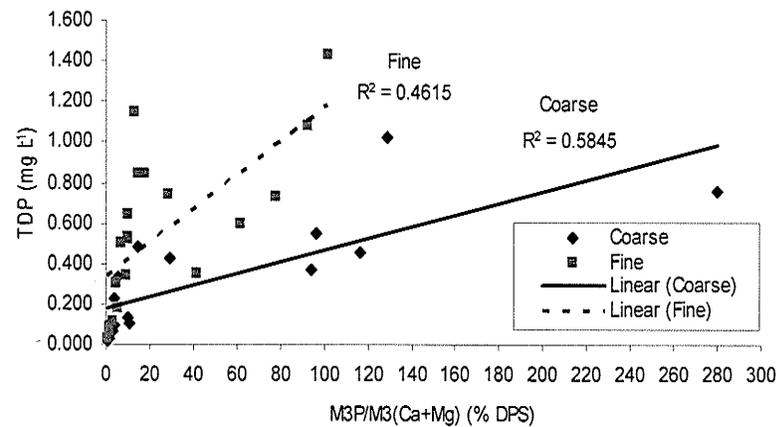
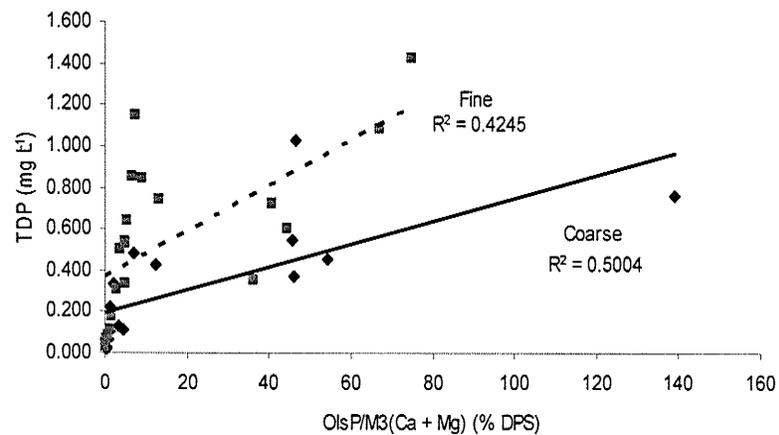
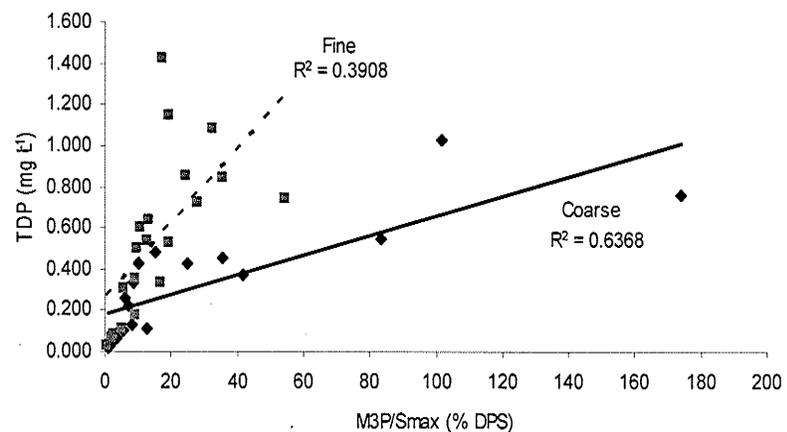
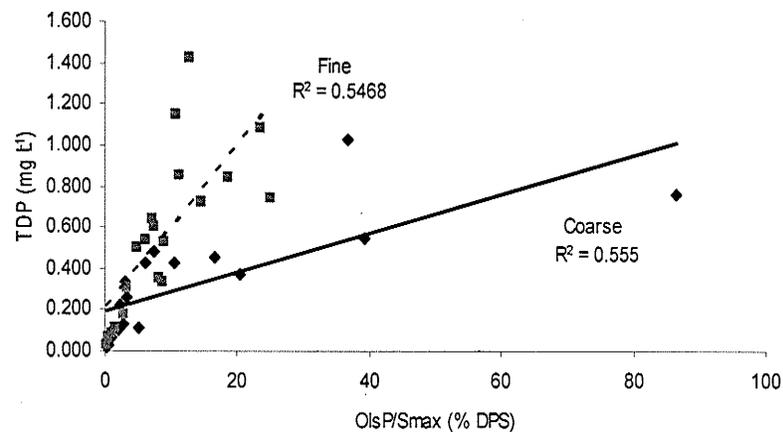


Fig X.3: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

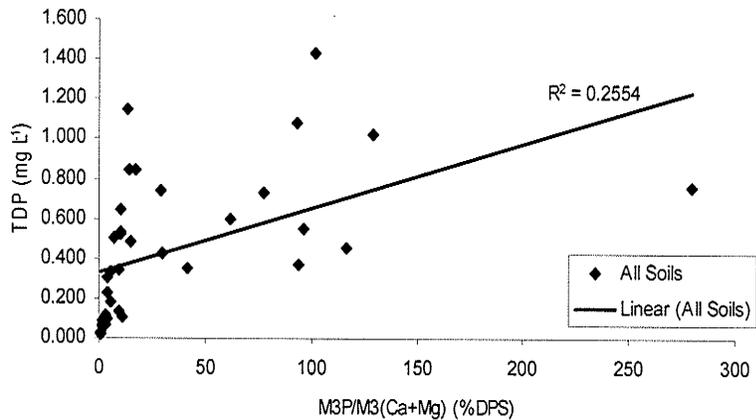
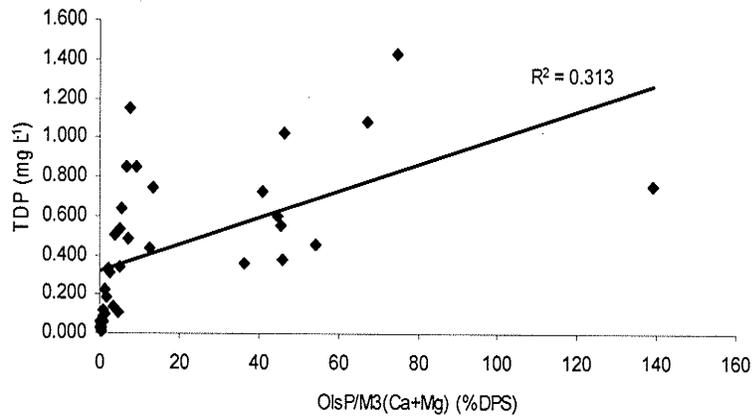
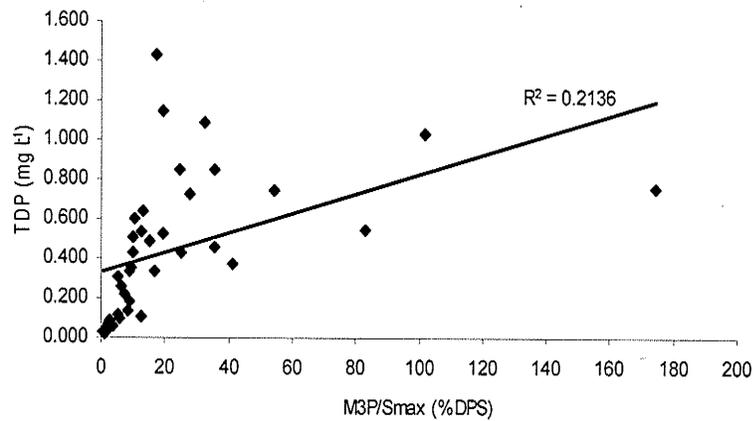
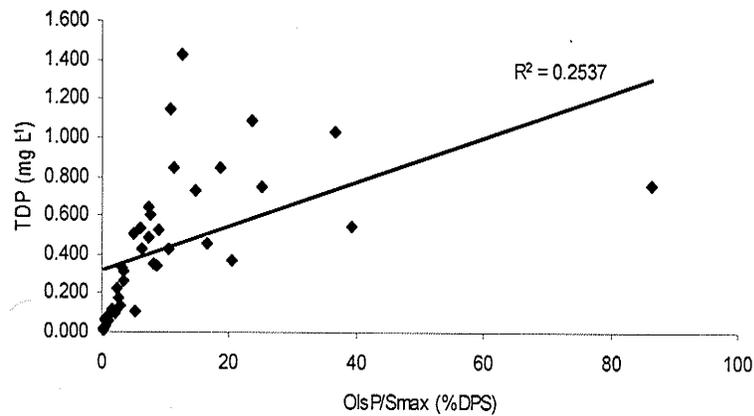


Fig X.4: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

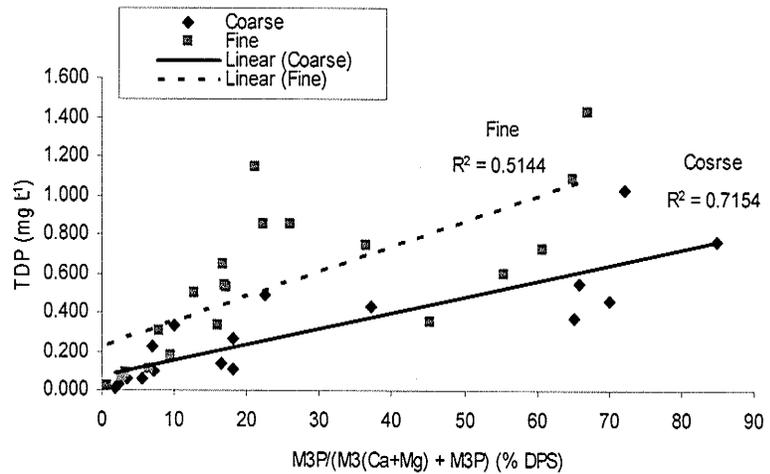
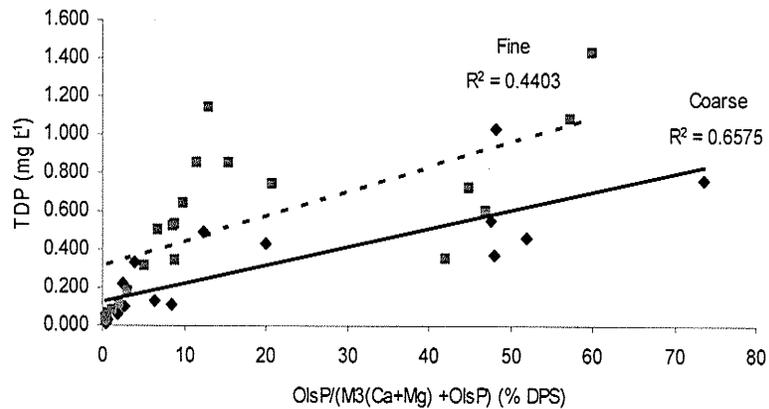
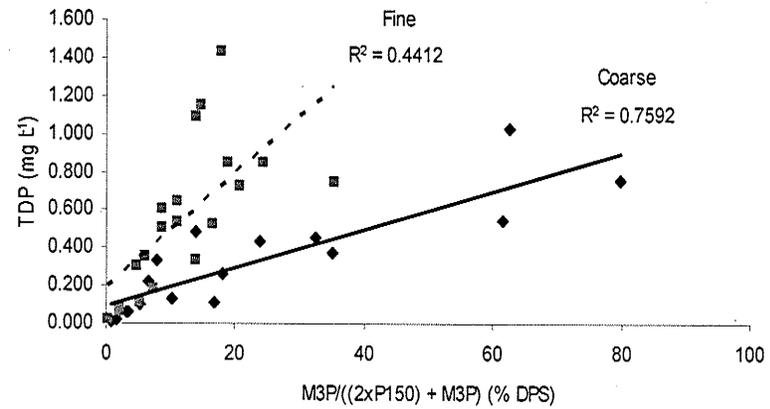
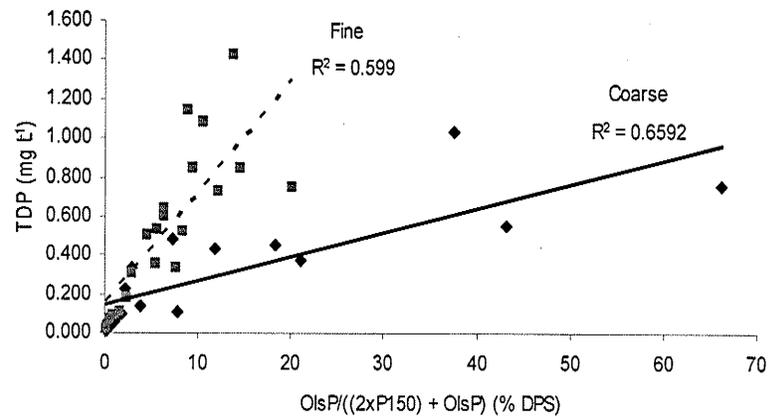


Fig X.5: Linear regression for soils grouped by texture for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

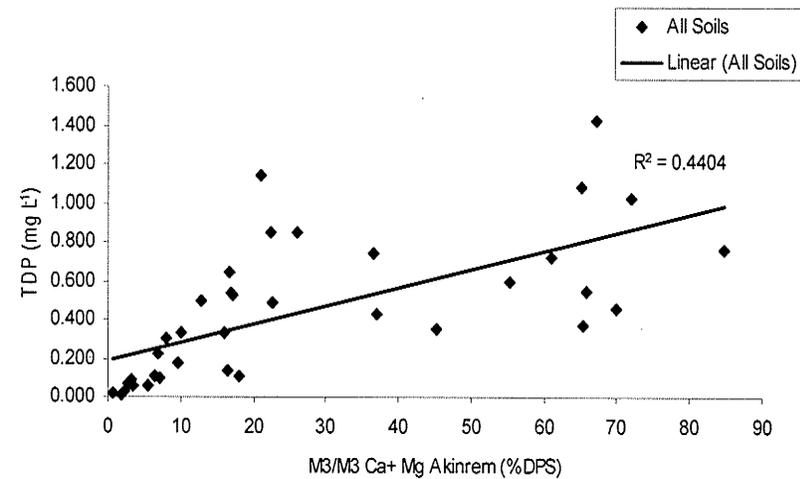
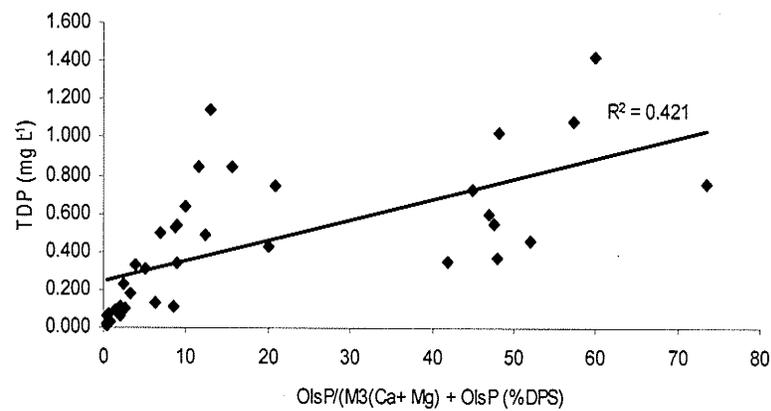
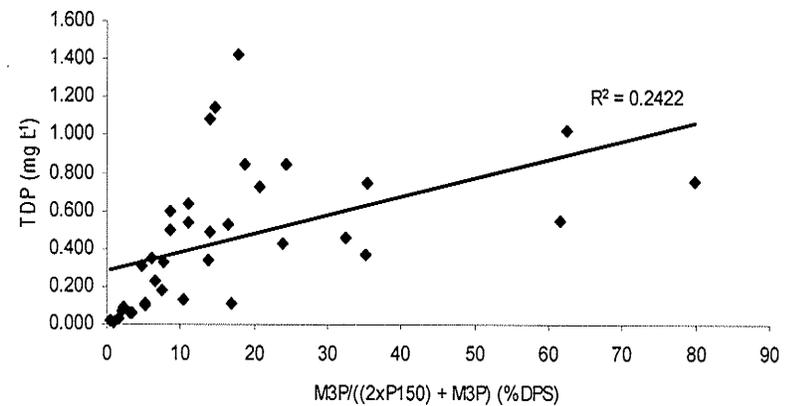
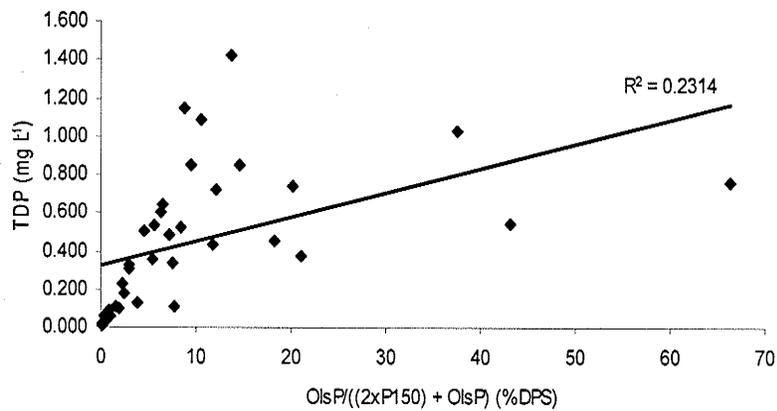


Fig X.6: Linear regression for all soils for with total dissolved P (TDP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

Table X.1: Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0231 a	0.0506	0.86 ***	<0.001	0.0181 a	0.2594	0.37 **	0.0047	0.0212	0.1455	0.52 ***	<0.0001	0.0273	0.1532	0.769 ***	<0.0001
Olsen (Ols-P)	0.0055 a†	0.1237	0.69 ***	<0.0001	0.0063 a	0.1231	0.73 ***	<0.0001	0.0061	0.1178	0.75 ***	<0.0001	0.0075	0.1442	0.815 ***	<0.0001
Modified Kelowna (MK-P)	0.0042 a	0.1122	0.82 ***	<0.0001	0.0040 a	0.2400 a	0.50 **	0.005	0.0043	0.1663	0.62 ***	<0.0001	0.0065	0.1425	0.777 ***	<0.0001
Mehlich 3 (M3-P)	0.0027 a	0.0968	0.77 ***	<0.0001	0.0032 a	0.1596	0.58 ***	<0.0001	0.0031	0.1191	0.65 ***	<0.0001	0.0044	0.0265	0.652 ***	<0.0001
Ols-P/(P150)	0.0094 a	0.196	0.56 ***	0.0004	0.0399 b	0.200	0.55 ***	0.0002	0.011	0.3190	0.25 **	0.0013	0.0179	0.322	0.255 ***	0.0009
M3-P/(P150)	0.0050 a	0.179	0.64 ***	<0.0001	0.0181 b	0.256	0.39 **	0.0032	0.005	0.3310	0.21 **	0.0035	0.0063	0.3890	0.130 *	0.0222
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0057 a§	0.1727	0.55 **	0.0017	0.0104 a	0.4010	0.41 **	0.0031	0.0067	0.3260 ¶	0.31 ***	0.0007	0.0110	0.2991	0.459 ***	<0.0001
M3-P/M3(Ca+Mg)α ₁	0.0030 a§	0.1524	0.64 ***	0.0004	0.0078 a	0.3708	0.44 **	0.0019	0.0031	0.3413 ¶	0.25 **	0.0027	0.0052	0.3530	0.274 **	0.0011
Ols-P/((2xP150)+Ols-P)	0.0118 a	0.1685	0.63 ***	<0.0001	0.0570 b	0.1486	0.60 ***	<0.0001	0.0129	0.3165	0.24 **	0.0020	0.0222	0.2982	0.285 ***	0.0004
M3-P/((2xP150)+M3-P)	0.0096 a	0.1202	0.71 ***	<0.0001	0.0300 b	0.1886	0.44 **	0.0014	0.0098	0.2840	0.25 **	0.0015	0.0149	0.2815	0.222 **	0.0022
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.0098 a§	0.1021	0.70 ***	<0.0001	0.013 a	0.3147	0.44 **	0.0014	0.0109	0.236 ¶	0.42 ***	<0.0001	0.0167	0.1960	0.431 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.0085 a§	0.0530	0.76 ***	<0.0001	0.0128 a	0.2272	0.52 ***	0.0004	0.0094	0.186 ¶	0.44 ***	<0.0001	0.0137	0.1502	0.357 ***	<0.0001
Ols-P/(PSI+Ols-P) ††	0.0076 a‡‡	0.1376	0.72 ***	<0.0001	0.0279 b	0.1295	0.61 ***	<0.0001	0.0090	0.2743 §§	0.31 ***	0.0003	0.0126	0.2903	0.236	0.0017
WEP/(PSI+WEP) ††	0.0103 a‡‡	0.1698	0.75 ***	<0.0001	0.0416 b	0.3559	0.22 *	0.0385	0.0087	0.3653 §§	0.16 *	0.0154	0.0181	0.3239	0.422 ***	<0.0001
MK-P/(PSI+MK-P) ††	0.0073 a‡‡	0.1262	0.72 ***	<0.0001	0.0216 b	0.1928	0.50 ***	0.0005	0.0083	0.2704 §§	0.30 ***	0.0005	0.0143	0.1995	0.436 ***	<0.0001
M3-P/(PSI+M3-P) ††	0.0073 a‡‡	0.0798	0.71 ***	<0.0001	0.0183 b	0.1183	0.51 ***	0.0004	0.0086	0.2063 §§	0.34 ***	0.0002	0.0141	0.1141	0.419 ***	<0.0001

*, **, *** significance at p<0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Appendix XI: STP and DPS regressions with PP for 0- 90 minute interval

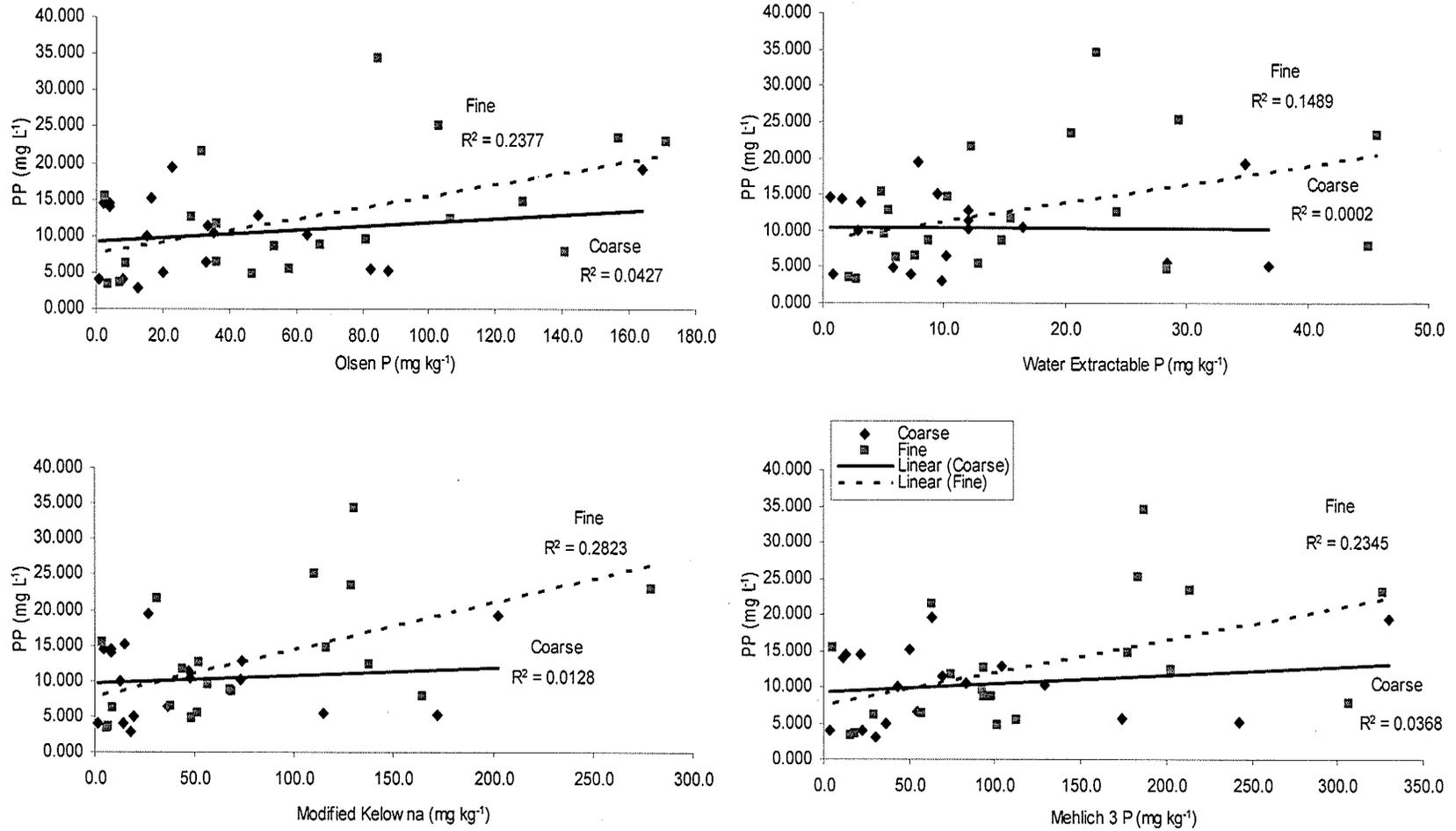


Fig XI.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 0-90 minutes of runoff.

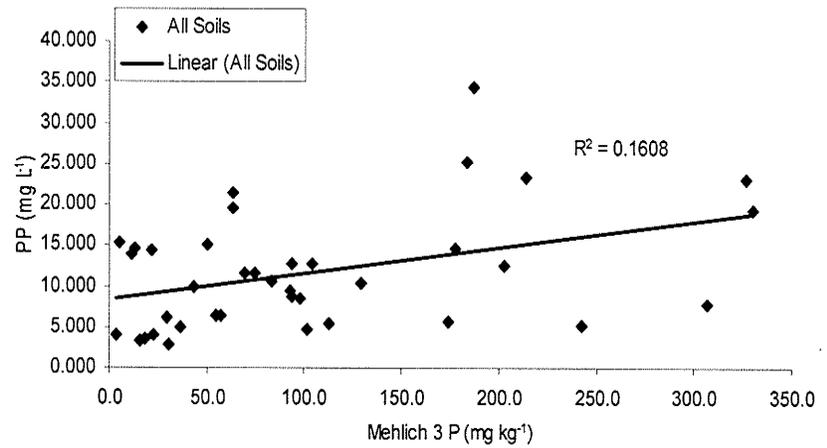
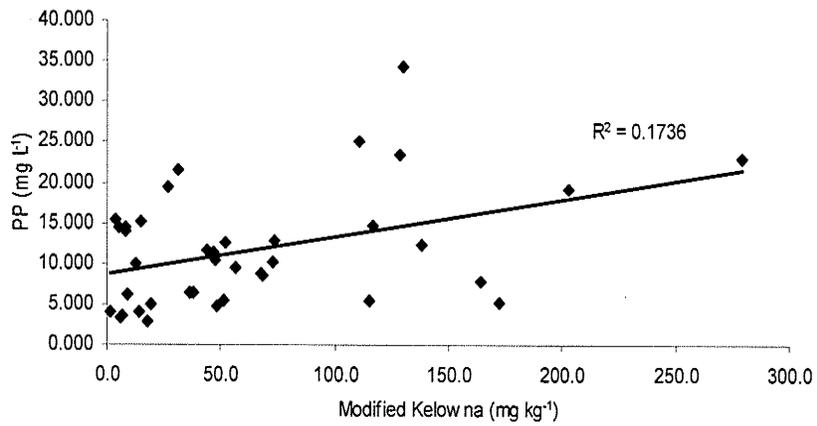
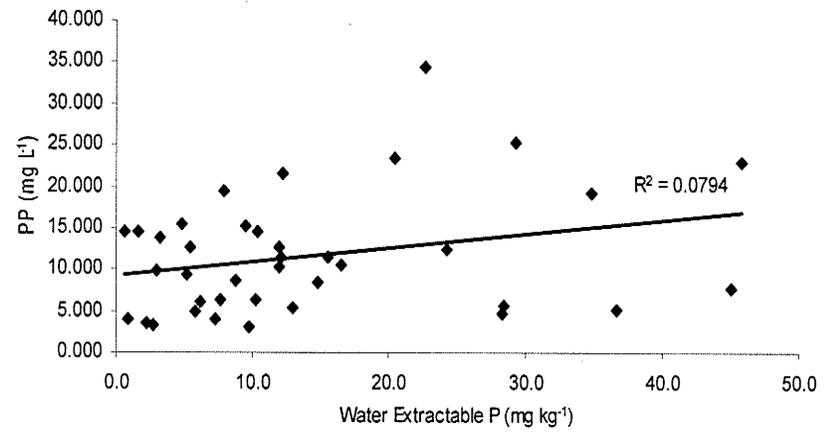
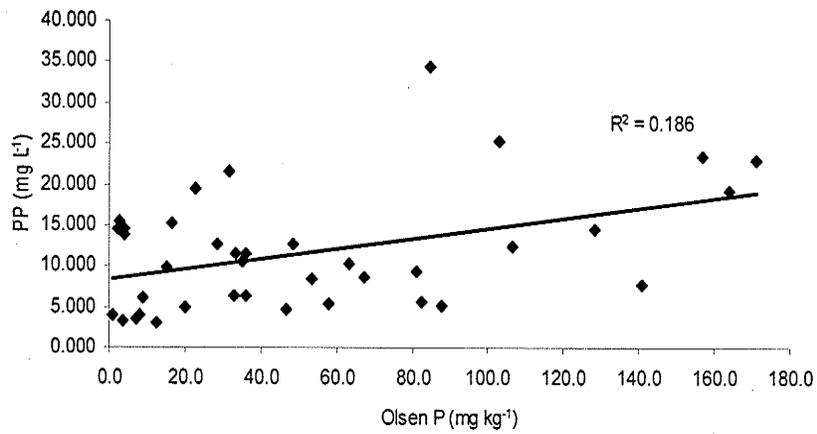


Fig XI.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with particulate P (PP) in 0-90 minutes of runoff.

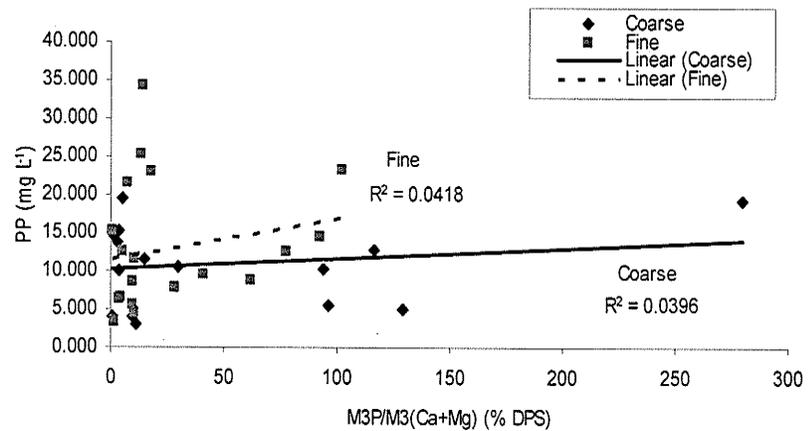
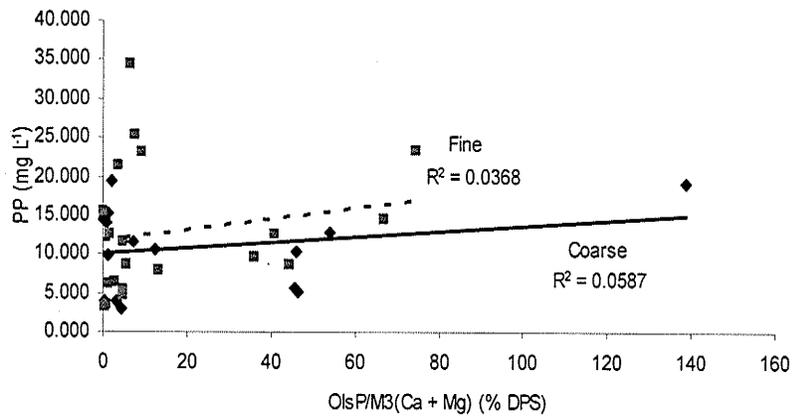
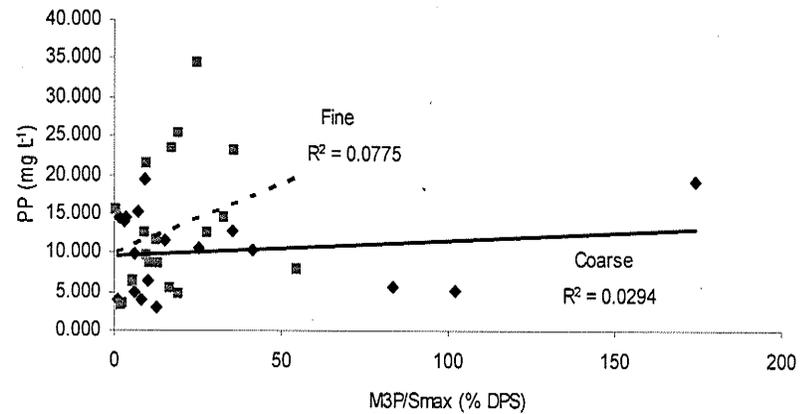
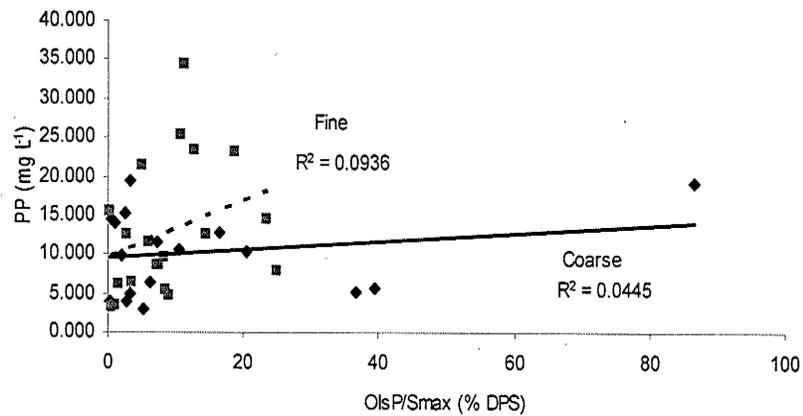


Fig XI.3: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

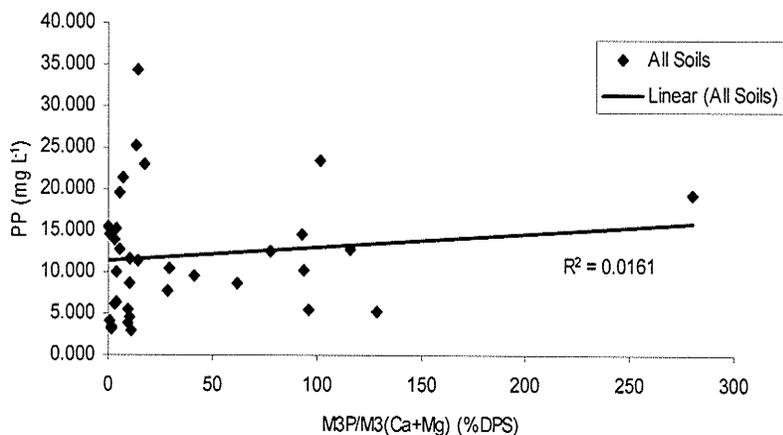
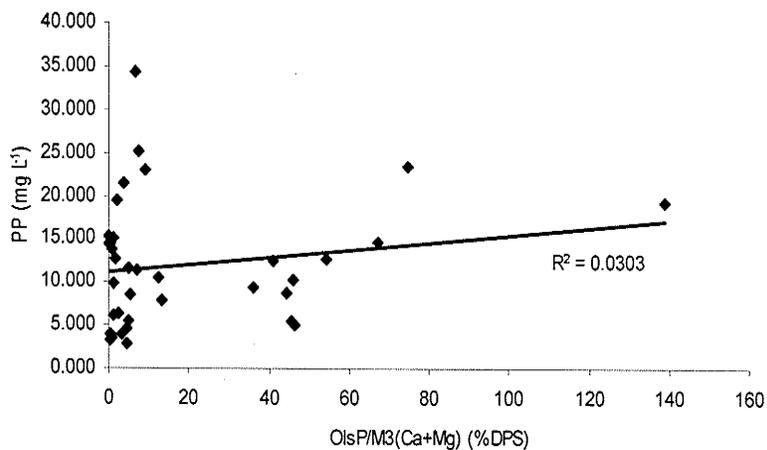
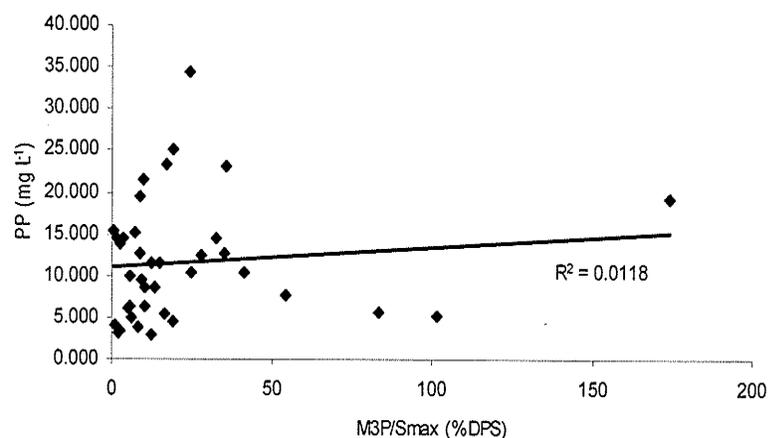
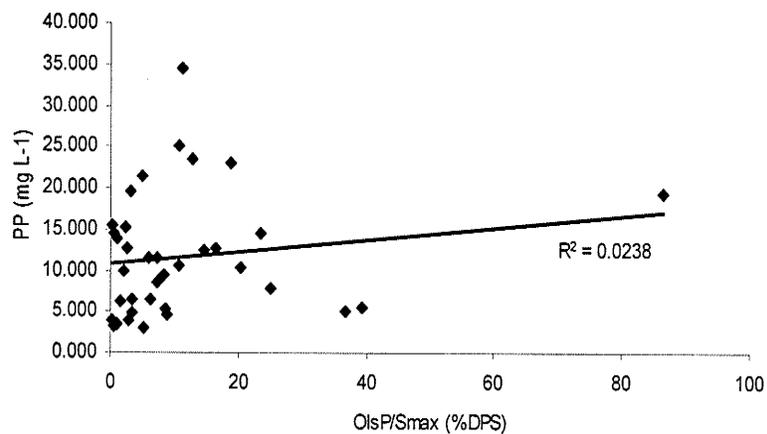


Fig XI.4: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

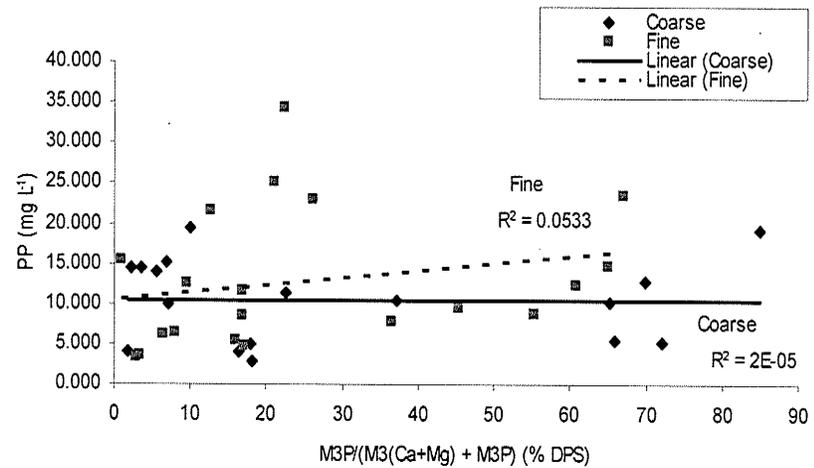
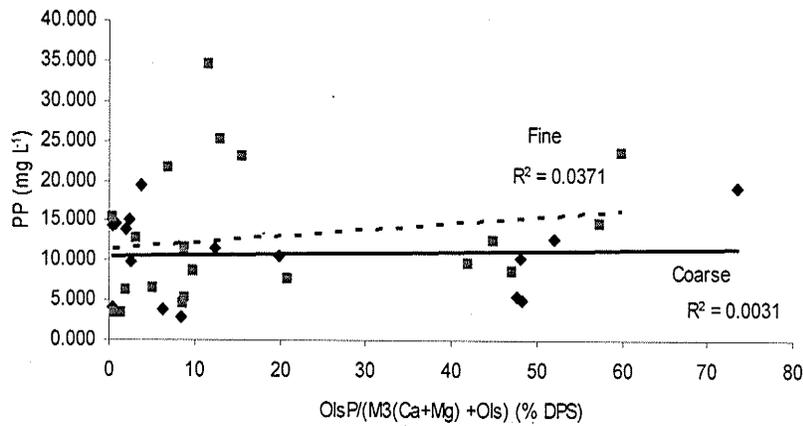
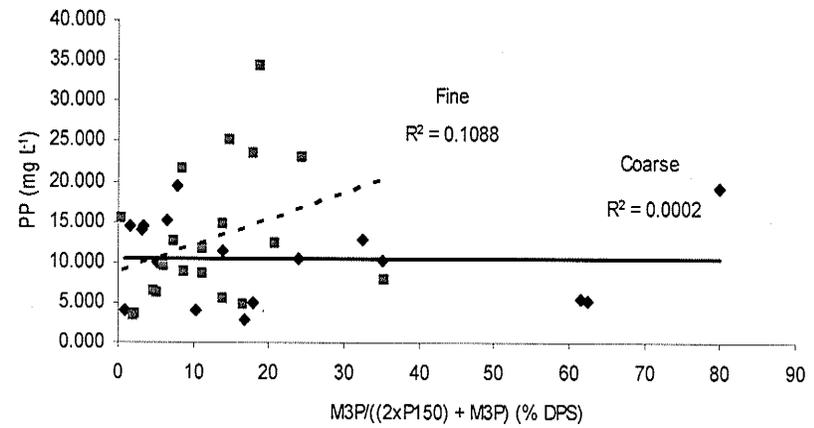
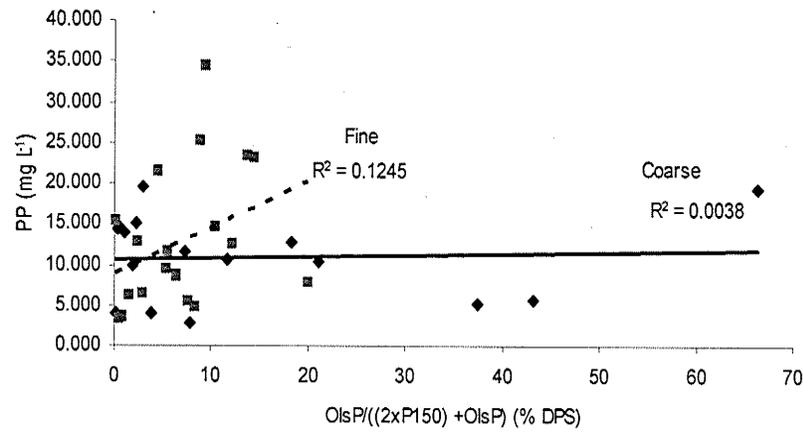


Fig XI.5: Linear regression for soils grouped by texture for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

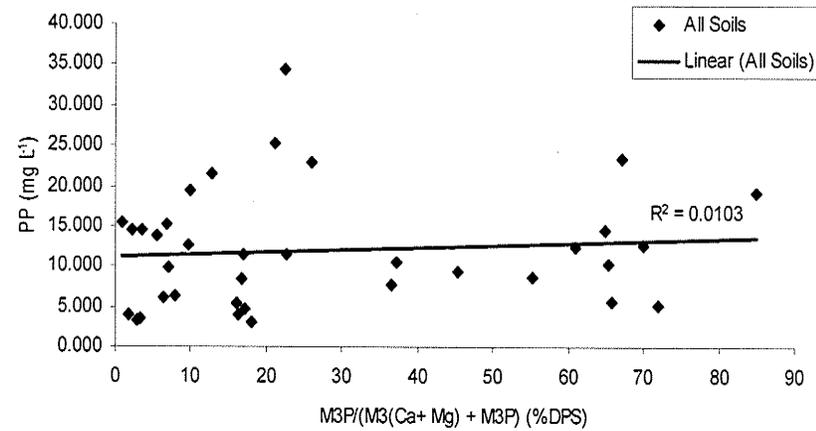
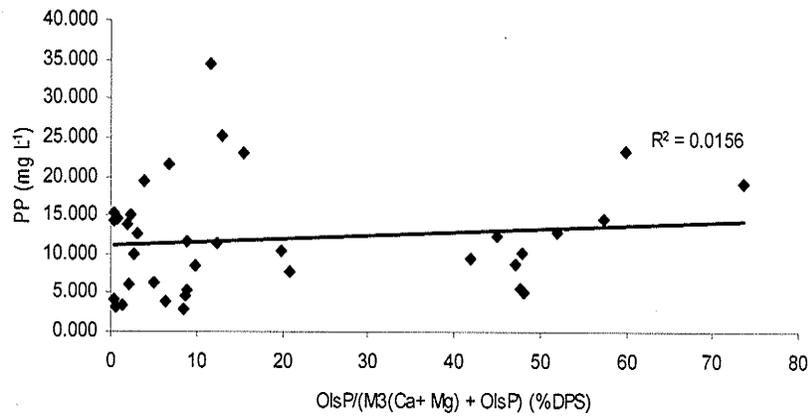
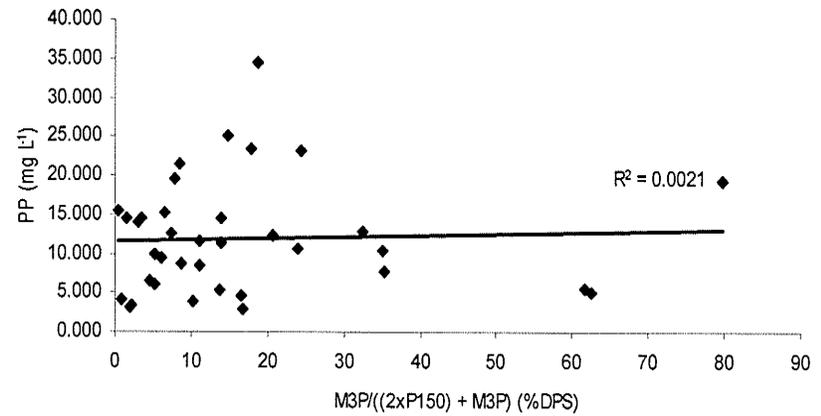
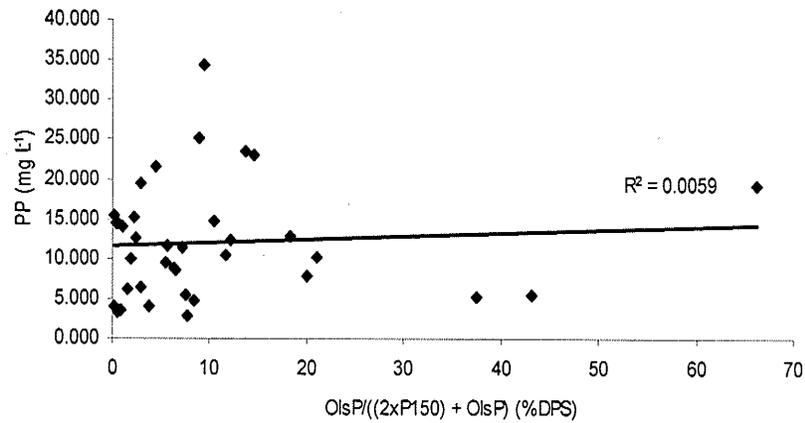


Fig X.6: Linear regression for all soils for with particulate P (PP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

Table XI.1: Linear regression for concentration of particulate P (PP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	-0.0063	10.318	0.0002	0.9591	0.2535	8.764	0.149	0.0929	0.1675	9.264	0.079	0.0865	0.121	9.833	0.100 *	0.0471
Olsen (OlsP)	0.0263	9.289	0.0427	0.411	0.0795	7.504	0.238 *	0.0292	0.0628	8.3130	0.186 *	0.0069	0.044	9.1390	0.180 *	0.0064
Modified Kelowna (MKP)	0.0102	9.737	0.013	0.6543	0.0665	7.720	0.282 *	0.0159	0.0467	8.634	0.174 *	0.0093	0.039	9.035	0.183 *	0.0059
Mehlich 3 (M3P)	0.0115	9.292	0.037	0.4454	0.045	7.358	0.234 *	0.0305	0.0318	8.339	0.161 *	0.0126	0.030	8.488	0.187 *	0.0053
OlsP/(P150)	0.0511	9.55	0.044	0.401	0.3622	9.660	0.094	0.1896	0.0704	10.85	0.024	0.3552	0.087	10.886	0.038	0.2284
M3P/(P150)	0.0197	9.648	0.029	0.4964	0.1773	9.974	0.078	0.2346	0.0235	11.091	0.012	0.5171	0.028	11.285	0.016	0.4403
OlsP/M3(Ca+Mg) α_1 †	0.0360 †	9.922	0.061	0.374	0.0773	11.405	0.043	0.396	0.0451 ¶	10.963	0.034	0.2968	0.040	11.265	0.037	0.261
M3P/M3(Ca+Mg) α_1	0.0143 †	10.027	0.042	0.4647	0.599	11.129	0.049	0.3619	0.0175 ¶	11.207	0.019	0.4416	0.018	11.472	0.021	0.3984
OlsP/((2xP150)+OlsP)	0.0322	9.823	0.013	0.6577	0.5703	8.828	0.125	0.127	0.0512	11.122	0.009	0.5715	0.071	11.174	0.018	0.4052
M3P/((2xP150)+M3P)	0.009	10.051	0.002	0.8693	0.327	8.902	0.109	0.1554	0.0273	11.182	0.005	0.6841	0.039	11.271	0.009	0.5503
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0130 †	10.504	0.003	0.8354	0.083	11.357	0.037	0.4156	0.0420 ¶	11.162	0.016	0.4758	0.047	11.29	0.023	0.3749
M3P/(M3(Ca+Mg) α_2 + M3P)	-0.0040 †	10.9	0.0005	0.9357	0.09	10.574	0.053	0.3274	0.0290 ¶	11.175	0.01	0.5625	0.034	11.306	0.015	0.4716
*	significant at p< 0.05															
**	significant at p< 0.005															
***	significant at p< 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix XII: STP and DPS regressions with TP for 0- 90 minute interval

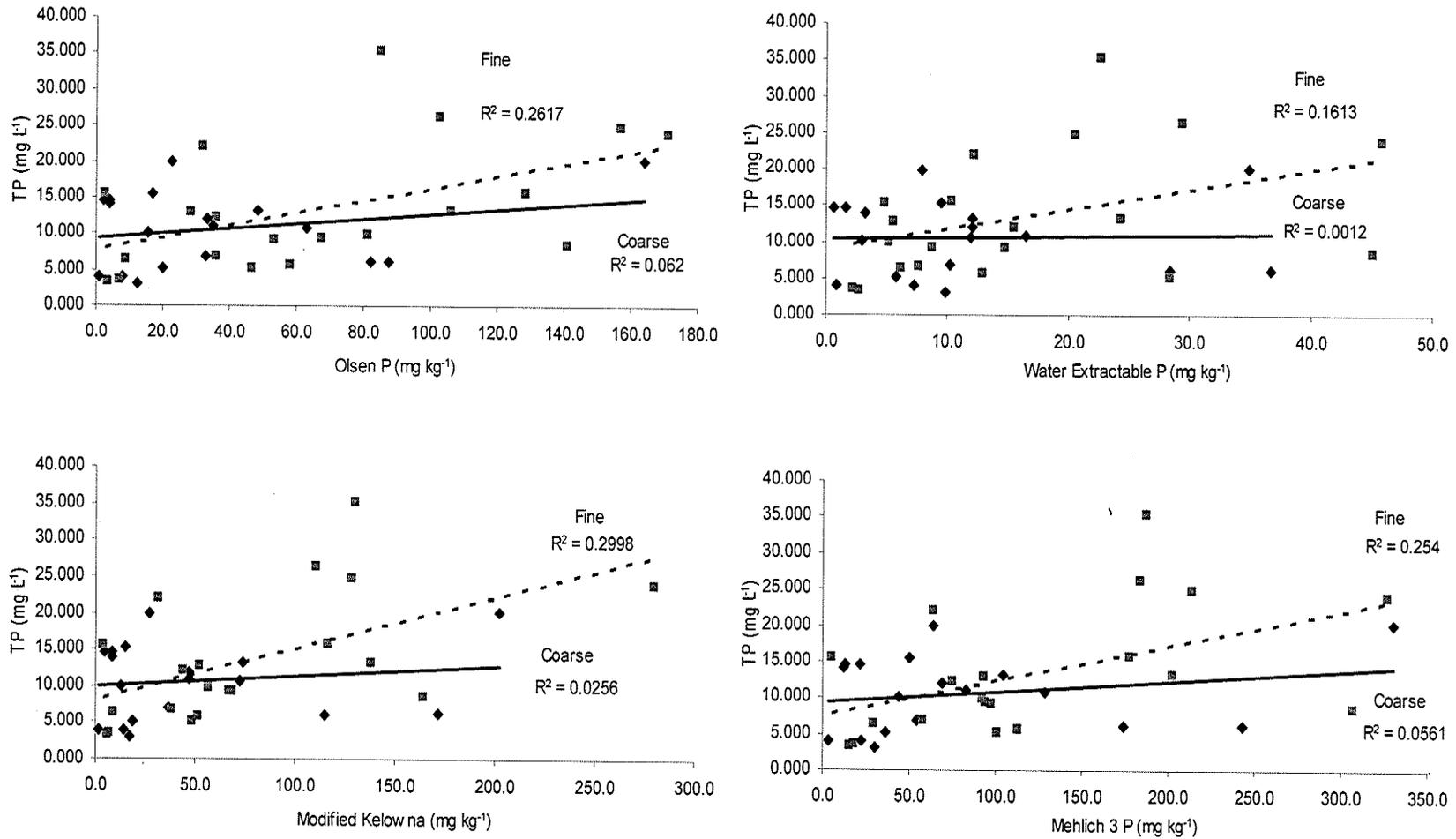


Fig XII.1: Linear regression for soils grouped by texture for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 0-90 minutes of runoff.

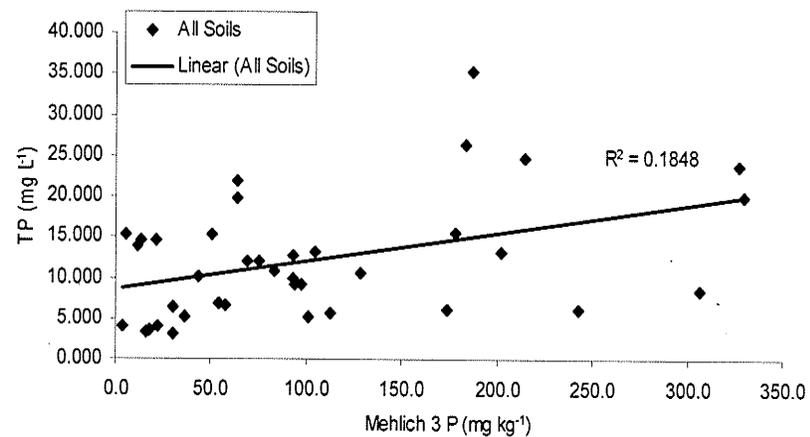
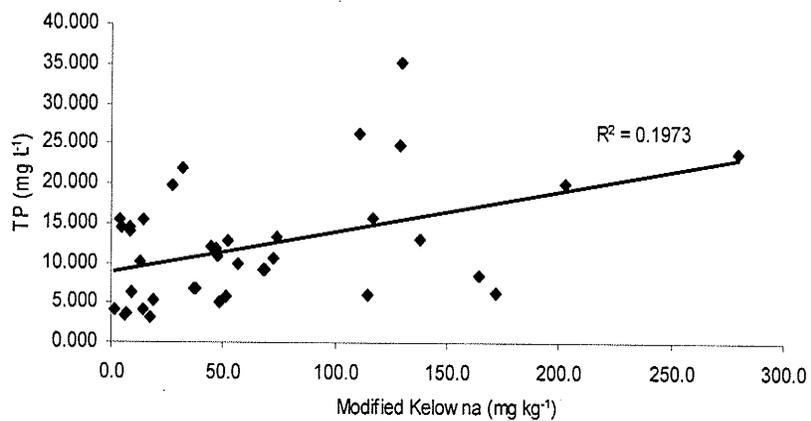
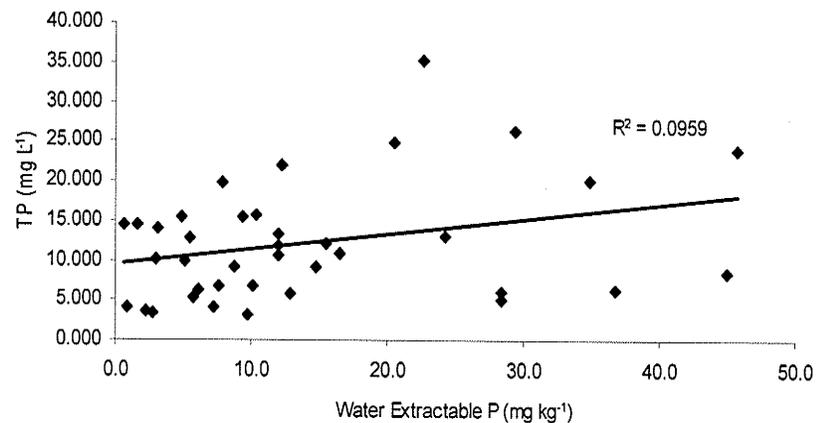
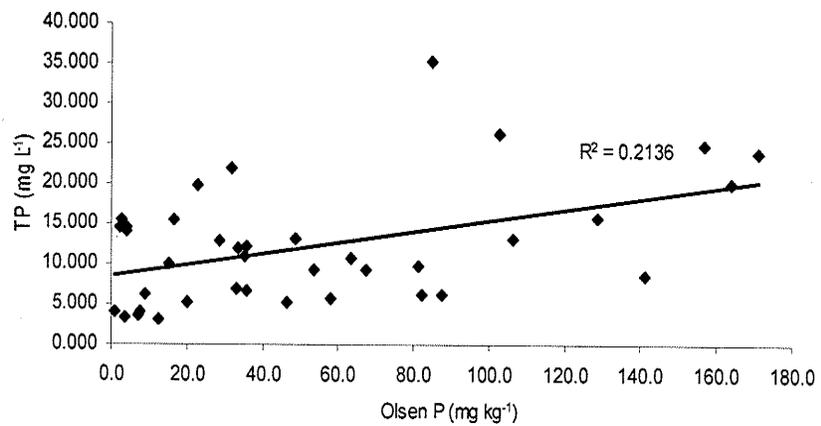


Fig XII.2: Linear regression for all soils for Olsen P, Water Extractable P, Modified Kelowna and Mehlich 3 P with total P (TP) in 0-90 minutes of runoff.

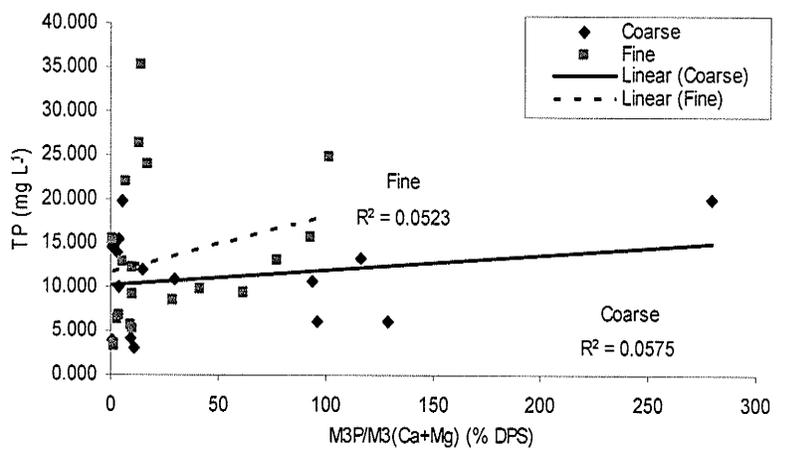
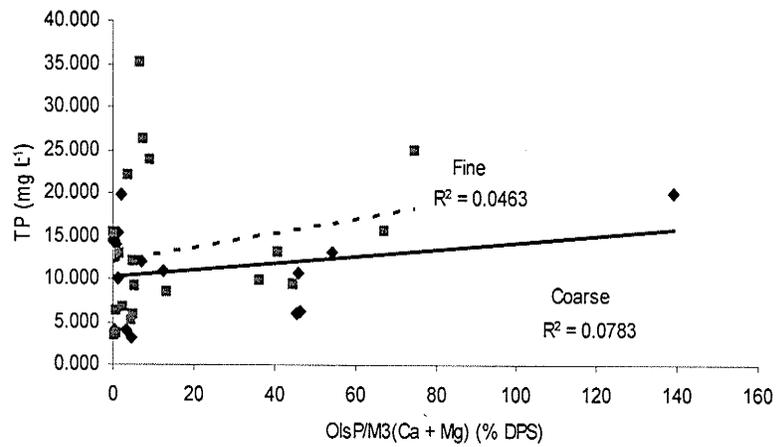
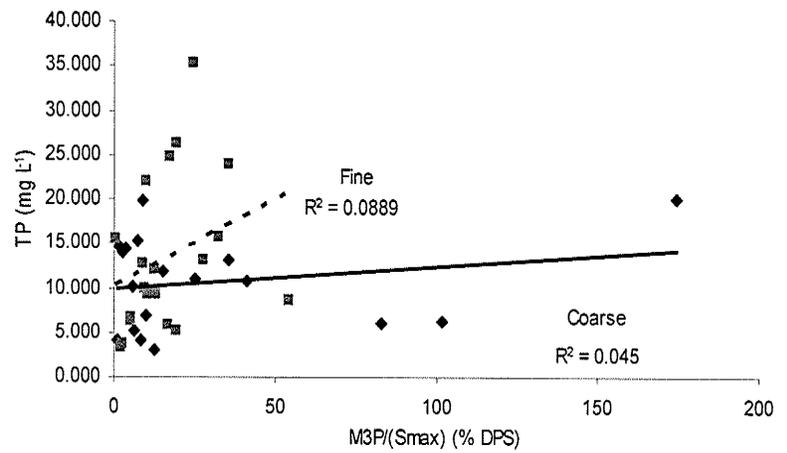
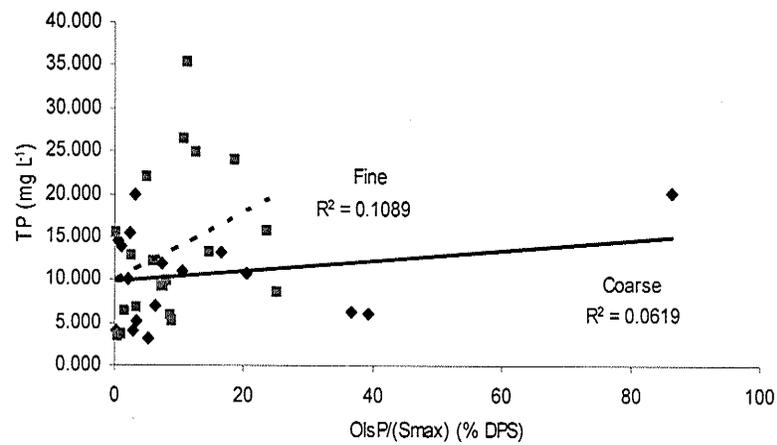


Fig XII.3: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

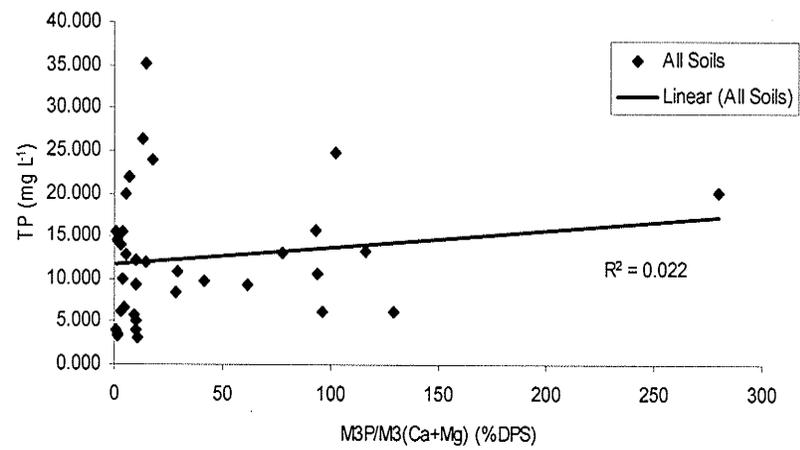
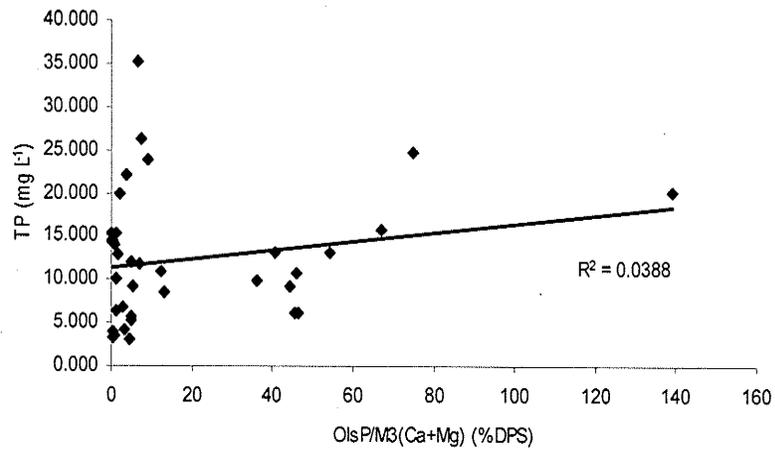
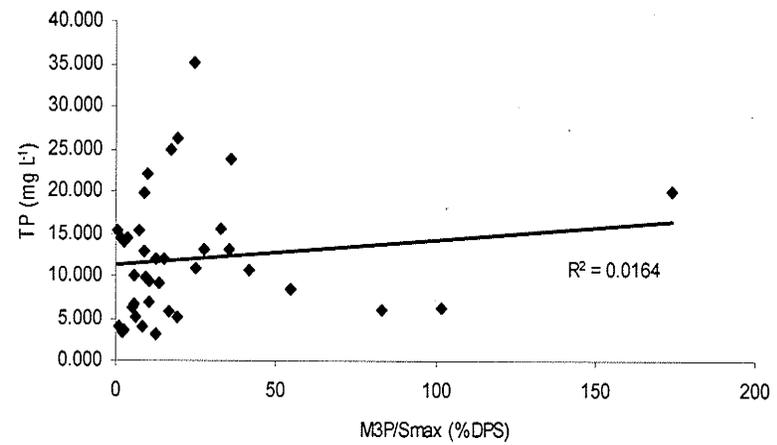
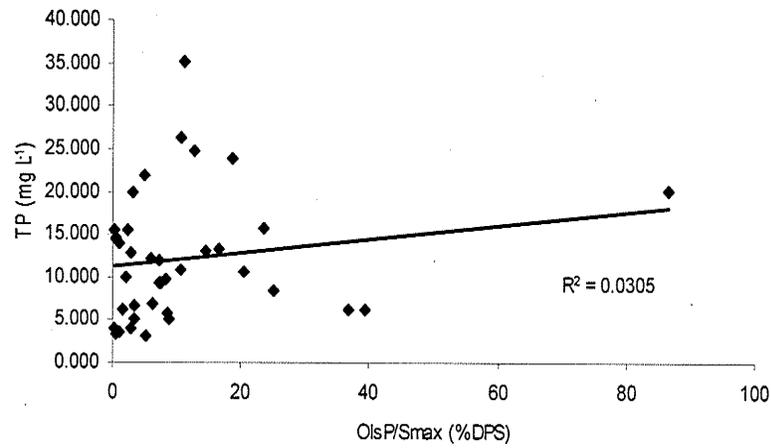


Fig XII.4: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) using molar ratios of Olsen P or Mehlich 3 P with P150 or Mehlich 3 extractable calcium and magnesium methods for the 0-90 minutes of runoff (Ige et al., 2005a).

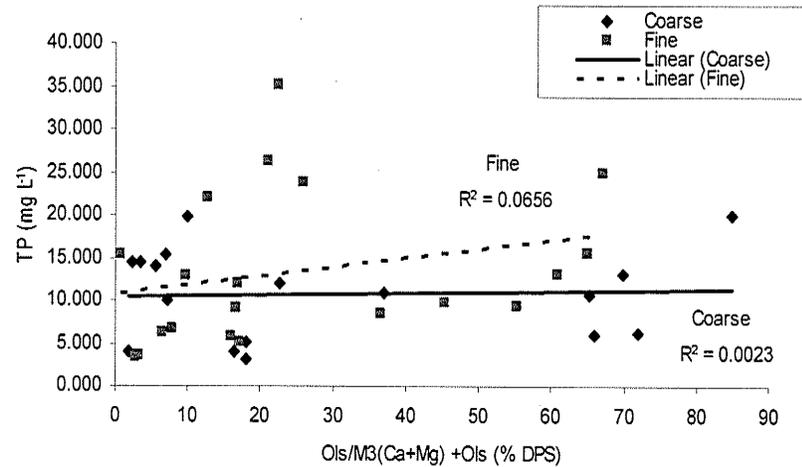
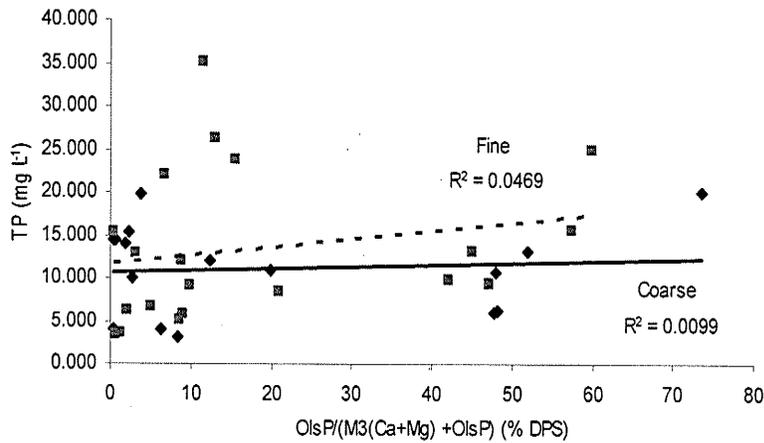
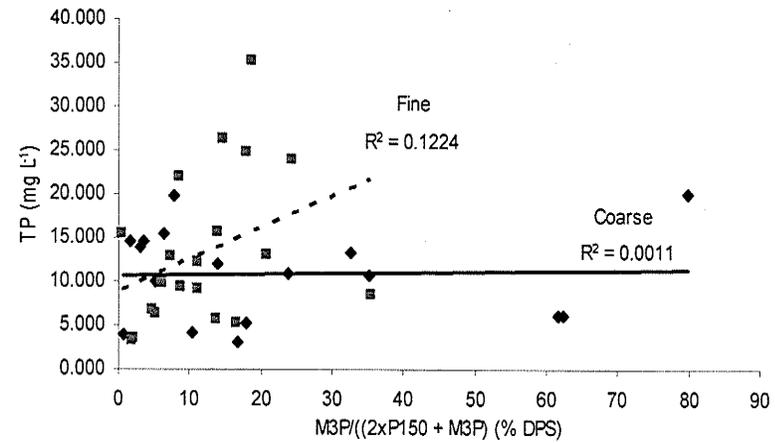
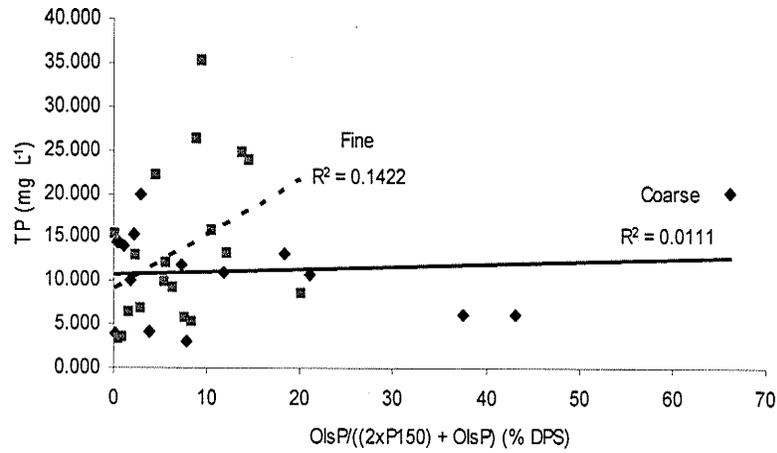


Fig XII.5: Linear regression for soils grouped by texture for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

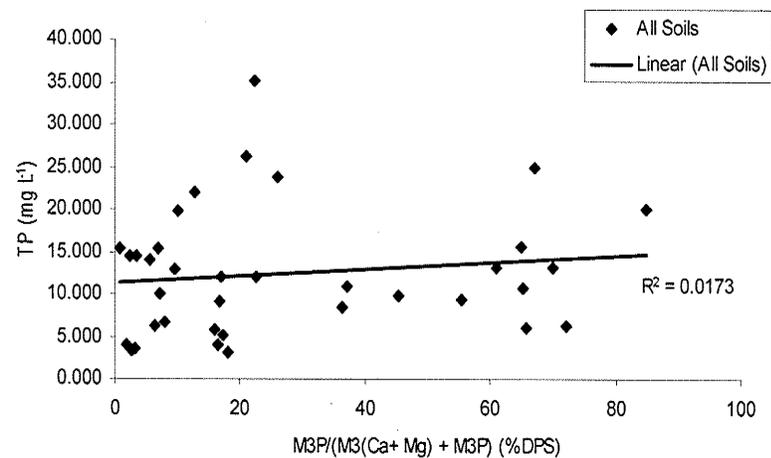
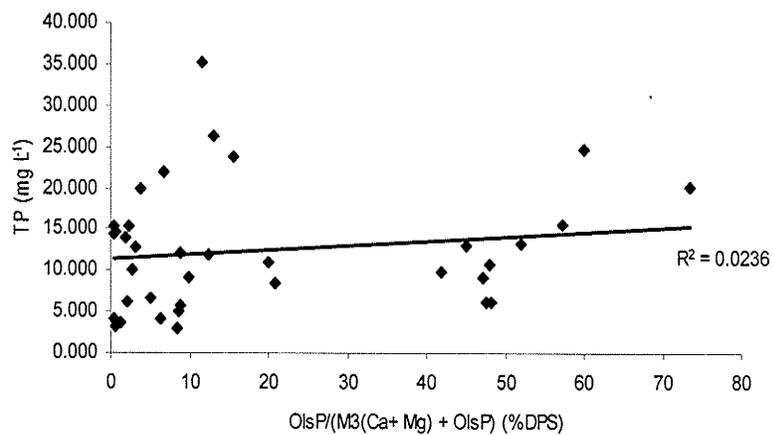
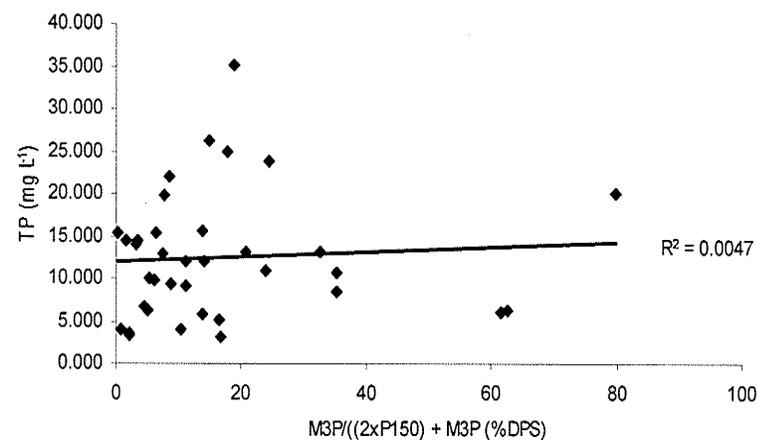
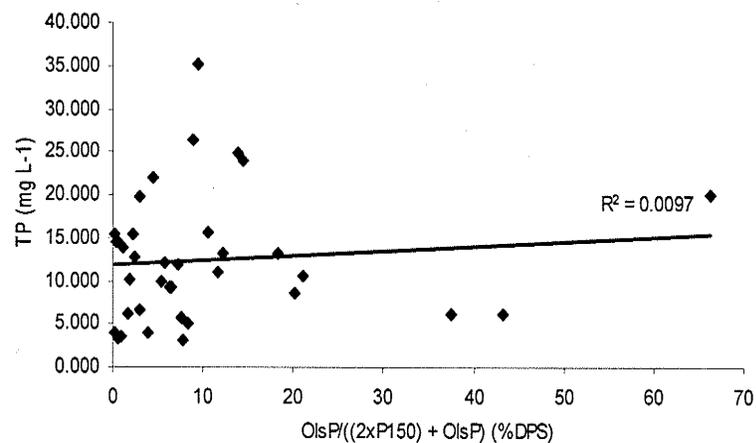


Fig XII.6: Linear regression for all soils for with total P (TP) and degree of P saturation (DPS) methods using molar ratios of Olsen P or Mehlich 3 P with P sorption maximum estimated from P150 isotherms or Mehlich 3 extractable calcium and magnesium for the 0-90 minutes of runoff (Akinremi et al., 2007).

Table XII.1: Linear regression for concentration of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-30 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.017	10.369	0.001	0.8904	0.272	9.023	0.161	0.0792	0.1887	9.410	0.096	0.0585	0.148	9.912	0.138	0.0182
Olsen (OlsP)	0.0317	9.413	0.062	0.3192	0.0858	7.627	0.262 *	0.0211	0.069	8.431	0.214 **	0.0035	0.0512	9.200	0.230 **	0.0017
Modified Kelowna (MKP)	0.0145	9.849	0.026	0.526	0.071	7.960	0.300 *	0.0125	0.051	8.800	0.197 *	0.0052	0.045	9.110	0.230 **	0.0018
Mehlich 3 (M3P)	0.0143	9.389	0.056	0.3439	0.0482	7.518	0.254 *	0.0235	0.035	8.458	0.185 *	0.0071	0.0342	8.515	0.230 **	0.0017
OlsP/(P150)	0.0605	9.746	0.062	0.3195	0.402	9.870	0.109	0.1554	0.0186	11.169	0.0305	0.2943	0.1052	11.207	0.052	0.1591
M3P/(P150)	0.0244	9.827	0.045	0.3979	0.1955	10.230	0.089	0.2017	0.0284	11.423	0.0163	0.444	0.034	11.674	0.022	0.359
OlsP/M3(Ca+Mg) α_1 †	0.042 †	10.094	0.082	0.301	0.088	11.806	0.052	0.3491	0.052 ¶	11.289	0.042	0.2422	0.052	11.560	0.057	0.1621
M3P/M3(Ca+Mg) α_1	0.0173 †	10.179	0.061	0.3755	0.017	10.178	0.061	0.3755	0.0207 ¶	11.548	0.025	0.3757	0.023	11.824	0.035	0.292
OlsP/((2xP150)+OlsP)	0.044	9.991	0.023	0.5448	0.627	8.976	0.142	0.1012	0.064	11.439	0.013	0.4891	0.093	11.472	0.029	0.2895
M3P/((2xP150)+M3P)	0.019	10.171	0.007	0.7364	0.3565	9.090	0.122	0.1304	0.0371	11.466	0.008	0.5896	0.054	11.553	0.017	0.4235
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.023 †	10.606	0.0107	0.7137	0.096	11.672	0.047	0.3509	0.0523 ¶	11.397	0.023	0.3795	0.064	11.485	0.039	0.244
M3P/(M3(Ca+Mg) α_2 + M3P)	0.004 †	10.952	0.0006	0.9326	0.1032	10.802	0.067	0.2759	0.038 ¶	11.361	0.017	0.4524	0.047	11.456	0.027	0.3268
*	significant at p < 0.05															
**	significant at p < 0.005															
***	significant at p < 0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Appendix XIII. Runoff Total Phosphorus

Total phosphorus (TP) is made up of total dissolved P (TDP) and particulate P (PP). Particulate phosphorus (PP) is seen as less environmentally significant because the P is bound to soil particles and is less biologically available (Uusitalo et al., 2001). Uusitalo et al. (2001) showed that when the majority of TP was made up of PP; TP was a poor predictor of P loading when they were studying algal available P. However, this material may still have P desorb into the freshwater systems (Uusitalo et al., 2001). In the runoff water collected from the Manitoba soils, 90% of TP is made up from PP and the correlations are in many cases improved when TDP is added. In a Minnesota study they found that TP was made up of 59-98% PP and others found that TP was 61-94% PP in packed soil boxes (Davis et al., 2005; Fang et al., 2002). In Manitoba TP is of little concern because the landscape is less variable and there is little potential for water to move quickly enough to cause water erosion. In Manitoba, 99% of the agricultural landscape has low to very low risk of water erodibility (van Vliet et al., 2005). In the rainfall simulations conducted on the Manitoba soils a 5% slope was used to ensure runoff even though this represents a very small portion of landscapes.

In the Manitoba data set, relationships are not present with TP. None of the methods used to measure P in soils were able to produce equations suitable for prediction purposes (Table 3.4). The fine textured soils were better correlated to TP in runoff with STP and DPS with MK-P being the most closely related at an $r^2 = 0.32$ during the first 30 minutes of runoff (Table 3.4). Schroeder et al. (2004) compared predictability SRP and TP using M3-P, WEP, Fe_2O_3 strips and DPS calculated using a molar ratio of oxalate extractable P to oxalate extractable Fe and Al. They found that the relationship was

slightly better using TP rather than just SRP alone (Schroeder et al., 2004). However, the soils used in the study conducted by Schroeder et al. (2004) were field plots; we used packed soil boxes that were sieved. The idea of sieving was to maintain a uniform aggregate size and help with minimizing any hydrological differences between soils (Wright et al., 2003), but with the extremely sandy soils they became structureless after sieving, and some of the fine soils may have altered the aggregates from balling if the moisture was higher than 20% by weight. Kleinman et al. (2004) showed that sieving soils may actually destroy the large aggregates and make a higher proportion of fine particles that are more easily transported. In our study some of the coarse soils that had a high proportion of silt seemed to have increased sheet flow with the silt clogging up the pores, this was also seen by Wright et al. (2006). When Kleinman et al. (2004) compared field plots to boxes and found the amount of suspended solids (SS) was much greater from the packed boxes also the percentage of SRP that made up the TP was lower from the packed boxes. They found very good relationships with the amount of SS to TP, and proposed that the use of an erosion predictor may be a better predictor of TP than a chemical analysis for P.

The total P (TP) data from our rainfall simulations is not useful for prediction of P losses. The use of TP is not suitable for agricultural Manitoba because of the relatively flat landscape that the runoff is snowmelt driven and does not have the erosive power to move soil particles.

Table XIII.1 Linear regression for total P (TP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the first 30 minutes of runoff from soils with Olsen P concentrations <200 mg kg⁻¹.

STP or DPS	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Olsen (OlsP)	0.0448	11.096	0.066	0.3044	0.082	8.803	0.197	0.0501	0.067	10.045	0.151 *	0.0161
Water (WEP)	0.0245	12.435	0.001	0.8836	0.3441	8.765	0.213 *	0.0404	0.225	10.407	0.102	0.0508
Modified Kelowna (MKP)	0.0226	11.601	0.033	0.4680	0.0800	8.126	0.319 *	0.0094	0.057	9.885	0.188 *	0.0065
Mehlich 3 (M3P)	0.0209	11.004	0.064	0.3117	0.0531	7.842	0.253 *	0.0237	0.039	9.571	0.170 *	0.0101
OlsP/(S _{max})	0.092	11.471	0.077	0.2656	0.402	10.790	0.09	0.2001	0.115	12.300	0.046	0.1983
M3P/(S _{max})	0.039	11.546	0.061	0.3237	0.229	10.592	0.101	0.1726	0.048	12.482	0.035	0.2623
OlsP/M3(Ca+Mg)α ₁ ‡	0.058 †	12.306	0.087	0.2866	0.011	14.104	0.001	0.9185	0.041 ¶	13.196	0.020	0.4253
M3P/M3(Ca+Mg)α ₁	0.025 †	12.404	0.067	0.3534	0.022	13.682	0.005	0.766	0.022 ¶	13.190	0.021	0.4171
OlsP/((2xP150)+OlsP)	0.075	11.742	0.036	0.4493	0.616	9.972	0.113	0.1472	0.101	12.578	0.024	0.3448
M3P/((2xP150)+M3P)	0.039	11.904	0.017	0.6102	0.4	9.479	0.127	0.1237	0.067	12.472	0.02	0.3947
OlsP/(M3(Ca+Mg)α ₂ + OlsP) §	0.0373 †	12.904	0.016	0.6563	0.036	13.695	0.005	0.7594	0.035 ¶	13.374	0.008	0.6082
M3P/(M3(Ca+Mg)α ₂ + M3P)	0.0124 †	13.306	0.003	0.8553	0.062	12.768	0.02	0.5569	0.030 ¶	13.219	0.008	0.6041

, * significance at p< 0.05, p<0.01, p<0.001

† n=16

‡ α₁ = 0.2

§ α₂ = 0.1

¶ n=36

Appendix XIV: Linear regression tables for percolate losses of TDP, PP, and TP

Table XIV.1: Linear regression for concentration of total dissolved P (TDP) in percolate with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.3679 a	-0.9354	0.57 ***	0.0007	0.0818 b	0.2375	0.65 ***	<0.0001	0.1735	-0.0510	0.30 ***	0.0006	0.0856	1.0189	0.1787 *	0.0082
Olsen (Ols-P)	0.0595 a†	1.3406	0.22	0.0707	0.0149 b	0.5552	0.35 *	0.0057	0.0219	1.2673	0.08	0.0974	0.0149	1.6446	0.07	0.1195
Modified Kelowna (MK-P)	0.0551 a	0.6871	0.36 *	0.0135	0.0112 b	0.6976	0.34 *	0.0073	0.0244	0.8419	0.16 *	0.0142	0.0184	1.1270	0.147 *	0.0175
Mehlich 3 (M3-P)	0.0332 a	0.6861	0.30 *	0.0298	0.0099 b	0.3504	0.48 ***	0.0007	0.0173	0.6100	0.16 *	0.0142	0.0145	0.8111	0.158 *	0.0134
Ols-P/(S _{max})	0.1084	1.9825	0.19	0.0876	0.1183	0.5166	0.42 **	0.002	0.1173	1.1151	0.23 **	0.003	0.1153	1.1120	0.239 **	0.0019
M3-P/(S _{max})	0.0608 a	1.5650	0.27 *	0.0392	0.0723 a	0.3812	0.54 ***	0.0002	0.0655	0.9013	0.32 ***	0.0003	0.0661	0.9277	0.324 ***	0.0002
Ols-P/M3(Ca+Mg)α ₁ ‡	0.0427 ‡	2.6000	0.08	0.2921	0.0064	1.4600	0.01	0.6382	0.034 ††	1.8013	0.07	0.1304	0.0292	1.9000	0.068	0.113
M3-P/M3(Ca+Mg)α ₁	0.0257 ‡	2.2903	0.12	0.1842	0.0079	1.1361	0.04	0.4148	0.0253 ††	1.5360	0.13 *	0.029	0.0240	1.6020	0.135 *	0.0232
Ols-P/((2xP150)+Ols-P)	0.169 a	1.1872	0.33 *	0.0192	0.1988 a	0.1527	0.64 ***	<0.0001	0.1793	0.6247	0.39 ***	<0.0001	0.1701	0.6495	0.381 ***	<0.0001
M3-P/((2xP150)+M3-P)	0.1504 a	0.1433	0.45 **	0.0047	0.1275 a	0.0121	0.70 ***	<0.0001	0.1510	-0.0939	0.49 ***	<0.0001	0.1484	-0.0837	0.496 ***	<0.0001
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.1095 ‡	1.3240	0.23	0.0625	0.0131	1.3232	0.04	0.4007	0.0677 ††	1.1470	0.14 **	0.025	0.0638	1.2130	0.143 *	0.019
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.1022 ‡	0.4482	0.30 *	0.0277	0.0195	1.0690	0.10	0.1652	0.0726 ††	0.4423	0.22 **	0.0037	0.0701	0.5091	0.226 **	0.0026
Ols-P/(Ols-P+PSI) ††	0.0800 a§	0.7267	0.35 *	0.0213	0.0937 a	0.1422	0.60 ***	<0.0001	0.0834 ††	0.4468	0.39 ***	<0.0001	0.0846	0.4545	0.404 ***	<0.0001
WEP/(WEP+PSI) ††	0.1433 a§	0.5315	0.62 ***	0.0005	0.2549 a	0.3561	0.71 ***	<0.0001	0.1442 ††	0.7252	0.62 ***	<0.0001	0.1013	0.9142	0.500 ***	<0.0001
MK-P/(MK-P+PSI) ††	0.0768 a§	0.6050	0.34 *	0.023	0.0786 a	0.2510	0.58 ***	0.0001	0.0785 ††	0.3843	0.38 ***	<0.0001	0.0681	0.5038	0.372 ***	<0.0001
M3-P/(M3-P+PSI) ††	0.0740 a§	0.2116	0.31 *	0.0311	0.0708 a	-0.1220	0.67 ***	<0.0001	0.0749 ††	-0.0479	0.37 ***	0.0001	0.0678	0.0712	0.366 ***	<0.0001

*, **, *** significance at p<0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP concentration) are not significantly different at p<0.05

‡ α1 = 0.2

§ n=16

¶ n=36

α2 = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table XIV.2: Linear regression for concentration of particulate P (PP) in percolate with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.0129	0.3592	0.096	0.2436	0.0026	0.389	0.013	0.6288	0.0058	0.3852	0.035	0.2753	0.045	-0.1113	0.474***	<0.0001
Olsen (OlsP)	0.0004	0.4988	0.002	0.8705	0.002	0.295	0.1317	0.1158	0.0011	0.4108*	0.0198	0.4127	0.011	-0.0455	0.406***	<0.0001
Modified Kelowna (MKP)	0.0007	0.4792	0.009	0.7335	0.0005	0.390	0.015	0.6089	0.0004	0.4392	0.006	0.6275	0.009	0.025	0.312***	0.0003
Mehlich 3 (M3P)	0.0003	0.492	0.003	0.8393	0.0001	0.358	0.035	0.427	0.0003	0.4316	0.007	0.6263	0.005	0.060	0.202**	0.0046
OlsP/(P150)	0.0008	0.5046	0.002	0.8821	0.004	0.395	0.009	0.6794	0.002	0.4499	0.005	0.6865	0.019	0.457	0.0638	0.1261
M3P/(P150)	0.0006	0.4961	0.004	0.8153	-0.0001	0.432	0.000	0.9875	0.0008	0.4485	0.006	0.6597	0.004	0.5975	0.0119	0.5148
OlsP/M3(Ca+Mg) α_1 ‡	-0.0008 †	0.5353	0.004	0.8202	0.0064	0.324	0.262*	0.021	0.0017 ¶	0.4356	0.018	0.4369	0.020	0.2616	0.292***	0.0005
M3P/M3(Ca+Mg) α_1	-0.0003 †	0.5298	0.002	0.8813	0.0042	0.321	0.222*	0.0361	0.0007 ¶	0.4432	0.011	0.5452	0.007	0.4086	0.120*	0.0332
OlsP/((2xP150)+OlsP)	0.003	0.4719	0.016	0.6373	0.016	0.314	0.089	0.201	0.005	0.4189	0.03	0.3097	0.031	0.3503	0.121*	0.0321
M3P/((2xP150)+M3P)	0.004	0.4254	0.044	0.4374	0.005	0.365	0.026	0.501	0.0045	0.3922	0.047	0.2024	0.019	0.3705	0.073	0.1009
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.0017 †	0.4822	0.007	0.7506	0.0074	0.294	0.258	0.0222	0.0044 ¶	0.384	0.062	0.1433	0.024	0.2036	0.1864*	0.0068
M3P/(M3(Ca+Mg) α_2 + M3P)	0.0030 †	0.4262	0.034	0.4886	0.0063	0.269	0.227	0.0336	0.0044 ¶	0.3459	0.088	0.079	0.018	0.1808	0.138*	0.0219
*	significant at p<0.05															
**	significant at p<0.005															
***	significant at p<0.001															
†	n=16															
‡	$\alpha_1 = 0.2$															
§	$\alpha_2 = 0.1$															
¶	n=36															

Table XIV.3: Linear regression for concentration of total P (TP) in percolate with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹				All Samples >200 Ols-P			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	R ²	Pr > F
Water (WEP)	0.381 a#	-0.576	0.559***	0.0009	0.0843 b	0.626	0.606***	<0.0001	0.179	0.334	0.288***	0.0007	0.131	0.907	0.334***	0.0001
Olsen (OlsP)	0.06	1.839	0.200	0.0826	0.0169	0.850	0.397**	0.0029	0.023	1.678	0.079	0.0967	0.026	1.538	0.181*	0.0078
Modified Kelowna (MKP)	0.056 a	1.166	0.341*	0.0175	0.0117 b	1.088	0.321*	0.0092	0.025	1.281	0.155*	0.0173	0.027	1.152	0.255**	0.0012
Mehlich 3 (M3P)	0.033 a	1.178	0.274**	0.0373	0.0104 a	0.708	0.468***	0.0009	0.0176	1.041	0.156*	0.0171	0.02	0.871	0.236**	0.002
OlsP/(P150)	0.1092	0.249	0.181	0.1009	0.122	0.912	0.392**	0.0031	0.119	1.565	0.217**	0.0042	0.135	1.568	0.26**	0.0011
M3P/(P150)	0.0615 a	2.061	0.252*	0.0474	0.072 a	0.813	0.472***	0.0008	0.066	1.350	0.299***	0.0006	0.0702	1.525	0.293***	0.0005
OlsP/M3(Ca+Mg) α_1 ‡	0.042 †	0.070	0.3238	0.3238	0.0127	1.784	0.044	0.3747	0.0357 ¶	2.237	0.066	0.1289	0.049	2.160	0.152*	0.0154
M3P/M3(Ca+Mg) α_1	0.0254 †	2.820	0.11	0.21	0.0121	1.683	0.077	0.2372	0.026 ¶	1.979	0.128	0.0323	0.0314	2.010	0.184*	0.0072
OlsP/((2xP150)+OlsP)	0.172 a	1.659	0.317*	0.0233	0.215 a	0.467	0.652***	<0.0001	0.184	1.043	0.371***	<0.0001	0.202	1.000	0.427***	<0.0001
M3P/((2xP150)+M3P)	0.154 a	0.568	0.431*	0.0057	0.133 a	0.377	0.663***	<0.0001	0.155	0.298	0.479***	<0.0001	0.167	0.287	0.502***	<0.0001
OlsP/(M3(Ca+Mg) α_2 + OlsP) §	0.111 †	1.805	0.214	0.0714	0.0205	1.618	0.084	0.2149	0.072 ¶	1.531	0.144*	0.0224	0.087	1.417	0.215**	0.0033
M3P/(M3(Ca+Mg) α_2 + M3P)	0.105 †	0.874	0.292*	0.0307	0.0257	1.338	0.159	0.0812	0.0771 ¶	0.788	0.229**	0.0032	0.0878	0.690	0.283***	0.0006

* significant at p< 0.05

** significant at p< 0.005

*** significant at p< 0.001

† n=16

‡ $\alpha_1 = 0.2$

§ $\alpha_2 = 0.1$

¶ n=36

Within rows values followed by the same letter (for each method of determining P concentration) are not significantly different at p<0.05

Appendix XV: Linear regression tables for load in runoff and percolate

Table XV.1: Linear regression for load of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-30 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.249 a	2.859	0.23 *	0.0437	0.359 a	5.415	0.35 *	0.0059	0.347	3.750	0.33 ***	0.0002
Olsen (Ols-P)	0.099 a†	2.181	0.52 ***	0.0007	0.126 a	0.237	0.70 ***	<0.0001	0.122	2.21	0.67 ***	<0.0001
Modified Kelowna (MK-P)	0.059 a	2.852	0.37 **	0.0073	0.078 a	5.165	0.46 **	0.0010	0.077	3.720	0.45 ***	<0.0001
Mehlich 3 (M3-P)	0.042 a	2.332	0.42 **	0.0037	0.065 a	3.213	0.58 ***	<0.0001	0.059	2.551	0.53 ***	<0.0001
Ols-P/(P150)	0.174 a	3.146	0.43 *	0.0056	0.916 b	3.126	0.70 ***	<0.0001	0.216	6.300	0.22 **	0.0044
M3-P/(P150)	0.077 a	3.165	0.37 *	0.0120	0.436 b	4.104	0.55 ***	0.0002	0.082	6.826	0.14 *	0.0266
Ols-P/M3(Ca+Mg)α ₁ ‡	0.128 a§	2.785	0.61 ***	0.0003	0.241 b	7.257	0.50 ***	0.0005	0.153 ¶	5.818	0.37 ***	<0.0001
M3-P/M3(Ca+Mg)α ₁	0.059 a§	2.728	0.57 ***	0.0007	0.189 b	6.381	0.59 ***	<0.0001	0.068 ¶	6.280	0.27 **	0.0013
Ols-P/((2xP150)+Ols-P)	0.195 a	2.937	0.39 *	0.0101	1.252 b	2.345	0.71 ***	<0.0001	0.215	6.578	0.15 *	0.0193
M3-P/((2xP150)+M3-P)	0.146 a	2.372	0.37 *	0.0132	0.686 b	2.887	0.57 ***	0.0001	0.153	6.181	0.14 *	0.0250
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.190 a§	1.784	0.60 ***	0.0005	0.295 b	5.808	0.56 ***	0.0002	0.231 ¶	4.301	0.44 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.147 a§	1.19	0.54 **	0.0011	0.297 b	3.658	0.68 ***	<0.0001	0.194 ¶	3.394	0.43	<0.0001
Ols-P/(PSI+Ols-P) ††	0.128 a‡‡	2.729	0.45 *	0.0063	0.624 b	1.760	0.75 ***	<0.0001	0.162 §§	5.835	0.24 **	0.0030
WEP/(PSI+WEP) ††	0.104 a‡‡	4.274	0.17	0.1309	1.011b	6.441	0.31 *	0.0104	0.079 §§	8.197	0.03	0.3157
MK-P/(PSI+MK-P) ††	0.127 a‡‡	2.403	0.48 **	0.0045	0.481 b	3.201	0.60 ***	<0.0001	0.152 §§	5.709	0.23 **	0.0033
M3-P/(PSI+M3-P) ††	0.135 a‡‡	1.338	0.53 **	0.0021	0.419 b	1.260	0.65 ***	<0.0001	0.169 §§	4.214	0.30 ***	0.0006

*, **, *** significance at p< 0.05, p<0.01, p<0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p<0.05

‡ α1 = 0.2

§ n=16

¶ n=36

α2 = 0.1

†† PSI = phosphorus saturation index determined using CaCl2 extraction containing 75 mg L-1 P as KH2PO4

‡‡ n=15

§§ n=35

Table XV.2: Linear regression for load of total dissolved P (TDP) in runoff with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS Method	Coarse Textured Group				Fine Textured Group				All Samples			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	0.515	8.080	0.187	0.0728	0.931	16.179	0.268 *	0.0194	0.875	10.803	0.260 **	0.0011
Olsen (Ols-P)	0.213 a†	6.402	0.458 **	0.0020	0.369 a	6.340	0.684 ***	<0.0001	0.337	5.365	0.642 ***	<0.0001
Modified Kelowna (MK-P)	0.125 a	7.943	0.313 *	0.0157	0.218 a	14.400	0.404 **	0.0026	0.202	10.188	0.39 ***	<0.0001
Mehlich 3 (M3-P)	0.088 a	6.871	0.352 *	0.0095	0.181 a	9.106	0.506 ***	0.0004	0.154	7.243	0.451 ***	0.0001
Ols-P/(P150)	0.372 a	8.181	0.381 *	0.0109	2.489 b	9.237	0.590 ***	<0.0001	0.487	17.859	0.136 *	0.0269
M3-P/(P150)	0.163 a	8.276	0.321 *	0.0222	1.106 b	13.171	0.403 **	0.0027	0.167	19.460	0.071	0.1161
Ols-P/M3(Ca+Mg)α ₁ ‡	0.280 a§	7.260	0.564 ***	0.0008	0.754 b	18.835	0.556 ***	0.0002	0.399 ¶	15.735	0.309 ***	0.0004
M3-P/M3(Ca+Mg)α ₁	0.129 a§	7.163	0.519 **	0.0016	0.566 b	16.734	0.605 ***	<0.0001	0.165 ¶	17.420	0.192 *	0.0074
Ols-P/((2xP150)+Ols-P)	0.418 a	7.735	0.340 *	0.0178	3.379 b	7.283	0.584 ***	<0.0001	0.461	18.730	0.087	0.0816
M3-P/((2xP150)+M3-P)	0.311 a	6.534	0.319 *	0.0225	1.749 b	9.981	0.417 **	0.0021	0.315	18.114	0.073	0.1101
Ols-P/(M3(Ca+Mg)α ₂ + Ols-P) #	0.419 a§	5.018	0.554 ***	0.0009	0.883 b	15.034	0.567 ***	0.0001	0.609 ¶	11.653	0.384 ***	<0.0001
M3-P/(M3(Ca+Mg)α ₂ + M3-P)	0.324 a§	3.719	0.506 **	0.0020	0.859 b	9.392	0.643 ***	<0.0001	0.496 ¶	9.668	0.354 ***	0.0001
Ols-P/(PSI+Ols-P) ††	0.271 a‡‡	7.313	0.388 *	0.0131	1.668 b	5.943	0.607 ***	<0.0001	0.361 §§	16.943	0.148 *	0.0226
WEP/(PSI+WEP) ††	0.207 ‡‡	10.804	0.127	0.1925	2.309	20.331	0.185	0.0584	0.108 §§	22.842	0.007	0.6288
MK-P/(PSI+MK-P) ††	0.274 a‡‡	6.546	0.420 *	0.0090	1.236 b	10.633	0.451 **	0.0012	0.333 §§	16.814	0.139 *	0.0271
M3-P/(PSI+M3-P) ††	0.292 a‡‡	4.207	0.472 **	0.0047	1.077 b	5.619	0.491 ***	0.0006	0.379 §§	13.278	0.190 *	0.0089

*, **, *** significance at p < 0.05, p < 0.01, p < 0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p < 0.05

‡ α₁ = 0.2

§ n=16

¶ n=36

α₂ = 0.1

†† PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

‡‡ n=15

§§ n=35

Table XV.3: Linear regression for load of total dissolved P (TDP) in percolate with methods of soil test P (STP) and degree of phosphorus saturation (DPS) for the 0-90 minute interval from soils with Olsen P concentrations <200 mg kg⁻¹ (n=18 coarse group, n=20 fine group).

STP or DPS	Coarse Textured Group				Fine Textured Group				All Samples <200 mg Olsen P kg ⁻¹			
	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F	Slope	Intercept	r ²	Pr > F
Water (WEP)	25.40 a†	-139.38	0.48 **	0.0029	0.708 b	4.07	0.32 *	0.0092	8.900	-43.63	0.15 *	0.0218
Olsen (OlsP)	3.76	31.07	0.15	0.0707	0.124	7.12	0.16	0.0786	0.817	40.78	0.02	0.0974
Modified Kelowna (MKP)	4.01	-37.92	0.34 *	0.0179	0.07	9.85	0.10	0.1843	1.320	-2.66	0.09	0.0746
Mehlich 3 (M3P)	2.35	-32.29	0.26 *	0.0433	0.08	5.99	0.20	0.0515	0.875	-8.34	0.08	0.0980
OlsP/(P150)	6.64	74.49	0.13	0.1722	0.93	7.32	0.17	0.0703	6.700	8.46	0.14 *	0.0242
M3P/(P150)	4.14	35.61	0.22	0.0669	0.557	6.44	0.21 *	0.0416	4.160	-13.63	0.24 **	0.0024
OlsP/M3(Ca+Mg) α_1 ¶	2.48	115.4	0.05	0.4192	0.035	14.99	0.002	0.8350	1.940	47.65	0.04	0.2414
M3P/M3(Ca+Mg) α_1	1.71 ‡	86.43	0.10	0.2426	0.042	14.49	0.01	0.7291	1.640	25.11	0.11	0.0540
OlsP/((2xP150)+OlsP)	10.56	22.82	0.23	0.0601	1.72	3.38	0.31 *	0.0106	10.640	-23.63	0.25 **	0.0018
M3P/((2xP150)+M3P)	9.82 a	-51.9	0.34 *	0.0186	1.07 b	2.53	0.32 **	0.0089	9.190	-70.23	0.34 ***	0.0002
OlsP/(M3(Ca+Mg) α_2 + OlsP) #	6.93 ‡	29.7	0.16	0.1247	0.082	14.05	0.01	0.6720	3.98 ††	8.14	0.09	0.0759
M3P/(M3(Ca+Mg) α_2 + M3P)	6.60 ‡	-29.81	0.22	0.0655	0.13	12.25	0.03	0.4615	4.30 ††	-34.23	0.15 *	0.0216
OlsP/(PSI+OlsP) §§	7.01 a§	-40.68	0.33 *	0.0262	0.77 b	3.88	0.27 *	0.0197	6.44 ‡‡	-58.52	0.31 ***	0.0005
WEP/(PSI+WEP)	13.13 a§	-66.59	0.64 ***	0.0003	2.12 b	5.52	0.32 **	0.0091	12.54 ‡‡	-49.83	0.64 ***	<0.0001
MKP/(PSI+MKP)	6.63 §	-48.81	0.31 *	0.0309	0.561	6.19	0.19	0.0532	5.90 ‡‡	-59.91	0.29 ***	0.0008
M3P/(PSI+M3P)	6.12 a	-76.550	0.27 *	0.0479	0.575 b	1.850	0.29 *	0.0144	5.23 ‡‡	-81.370	0.24 **	0.0027

*, **, *** significance at p < 0.05, p < 0.01, p < 0.001 respectively

† Within rows, values followed by the same letter (for each method of determining TDP load) are not significantly different at p < 0.05

‡ n=14

§ n=13

¶ $\alpha_1 = 0.2$

$\alpha_2 = 0.1$

†† n=34

‡‡ n=33

§§ PSI = phosphorus saturation index determined using CaCl₂ extraction containing 75 mg L⁻¹ P as KH₂PO₄

Appendix XVI: Raw data of runoff and percolate water and soil characteristics

Table XVI.1: Raw data for coarse textured soils

Soil Id		Total Dissolved P (mg L ⁻¹)							
		Run 1				Run 2			
		0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
C1	M 33	0.015	0.013	0.014	0.05	0.02	0.011	0.013	0.03
C2	M 25	0.071	0.053	0.053	0.138	0.073	0.06	0.059	0.247
C3	N 43	0.065	0.06	0.063	0.09	0.059	0.062	0.065	0.173
C4	N 32	0.026	0.027	0.025	0.042	0.022	0.026	0.025	0.06
C5	N 33	0.159	0.127	0.185	1.176	0.148	0.102	0.084	1.48
C6	M 26	0.184	0.11	0.074	7.777	0.226	0.098	0.073	7.216
C7	N 41	0.119	0.087	0.093	0.132	0.107	0.095	0.093	0.141
C8	N 133	0.281	0.243	0.171	0.724	0.268	0.199	0.185	0.872
C9	CT	0.422	0.334	0.375	n/a	0.301	0.247	0.212	n/a
C10	N 38	0.384	0.293	0.323	0.827	0.387	0.315	0.286	0.846
C11	ZT	0.457	0.42	0.475	n/a	0.787	0.564	0.335	n/a
C12	M 37	0.569	0.372	0.278	1.083	0.576	0.625	0.517	3.281
C13	N 36	0.494	0.341	0.28	5.337	0.789	0.425	0.299	3.999
C14	M202	0.577	0.487	0.328	0.928	0.474	0.367	0.411	1.873
C15	M203	0.482	0.441	0.336	1.004	0.486	0.268	0.274	1.322
C16	M200	1.062	0.668	0.404	18.413	0.75	0.409	0.315	15.925
C17	M201	1.595	0.763	1.124	18.461	1.084	0.733	0.636	15.413
C18	M204	0.911	0.531	0.501	3.8	1.113	0.762	0.714	1.512

Soil Id		Particulate P (mg L ⁻¹)							
		Run 1				Run 2			
		0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
C1		6.72	2.643	2.292	0.039	5.43	3.4	3.671	0.258
C2		14.525	11.542	5.358	0.154	39.165	8.006	9.922	0.186
C3		19.402	11.616	21.888	0.375	6.005	10.704	13.4	0.348
C4		11.975	7.89	9.282	0.186	25.491	15.964	15.784	0.152
C5		3.463	3.613	3.579	1.62	3.311	4.099	5.169	0.623
C6		1.824	2.525	2.151	1.181	2.668	3.366	4.239	0.906
C7		14.578	3.398	9.91	0.231	10.836	11.929	8.971	0.102
C8		14.915	23.779	9.641	0.269	10.707	12.831	18.7	0.124
C9		6.005	3.718	7.667	n/a	6.847	7.656	5.991	n/a
C10		24.639	24.062	21.018	0.193	18.501	15.702	13.208	0.149
C11		5.52	6.155	6.952	n/a	9.518	12.698	5.991	n/a
C12		13.882	11.941	7.8	0.234	7.237	8.9	18.784	0.739
C13		7.241	6.792	4.137	1.784	25.384	12.637	8.221	1.718
C14		16.674	15.685	6.746	0.176	12.523	3.661	21.601	0.317
C15		12.557	14.097	9.683	0.296	14.165	3.832	6.547	0.28
C16		5.086	5.311	3.687	0.754	8.84	7.632	4.53	1.4
C17		10.859	0.739	4.296	3.304	1.69	0.552	6.672	2.828
C18		24.481	14.919	17.625	0.288	24.882	14.235	19.306	0.163

Total P (mg L ⁻¹)								
Soil Id	Run 1				Run 2			
	0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
C1	6.735	2.656	2.306	0.089	5.45	3.411	3.684	0.288
C2	14.596	11.595	5.411	0.292	39.238	8.066	9.981	0.433
C3	19.467	11.676	21.951	0.465	6.064	10.766	13.465	0.521
C4	12.001	7.917	9.307	0.228	25.513	15.99	15.809	0.212
C5	3.622	3.74	3.764	2.796	3.459	4.201	5.253	2.103
C6	2.008	2.635	2.225	8.958	2.894	3.464	4.312	8.122
C7	14.697	3.485	10.003	0.363	10.943	12.024	9.064	0.243
C8	15.196	24.022	9.812	0.993	10.975	13.03	18.885	0.996
C9	6.427	4.052	8.042	n/a	7.148	7.903	6.203	n/a
C10	25.023	24.355	21.341	1.02	18.888	16.017	13.494	0.995
C11	5.977	6.575	7.427	n/a	10.305	13.262	6.326	n/a
C12	14.451	12.313	8.078	1.317	7.813	9.525	19.301	4.02
C13	7.735	7.133	4.417	7.121	26.173	13.062	8.52	5.717
C14	17.251	16.172	7.074	1.104	12.997	4.028	22.012	2.19
C15	13.039	14.538	10.019	1.3	14.651	4.1	6.821	1.602
C16	6.148	5.979	4.091	19.167	9.59	8.041	4.845	17.325
C17	12.454	1.502	5.42	21.765	2.774	1.285	7.308	18.241
C18	25.392	15.45	18.126	4.088	25.995	14.997	20.02	1.675

Volume (L)								
Soil Id	Run 1				Run 2			
	0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
C1	33.6	35.926	39.775	6.186	33.208	33.64	28.45	4.714
C2	13.43	14.806	13.898	7.912	16.318	17.954	18.258	5.358
C3	14.795	14.216	14.866	8.536	13.77	17.316	17.468	9.696
C4	14.318	13.292	14.13	3.968	18.39	16.824	16.944	4.062
C5	12.108	13.538	13.384	7.842	9.574	14.188	14.526	15.398
C6	2.132	5.532	8.484	30.52	6.182	9.522	12.428	48.122
C7	14.812	13.68	14.404	5.36	14.004	15.096	15.434	6.116
C8	13.388	14.216	13.746	6.716	11.758	12.386	12.79	9.178
C9	20.648	22.382	25.85	n/a	20.742	19.834	20.034	n/a
C10	20.314	19.356	20.038	4.28	15.052	16.54	17.206	3.562
C11	13.01	13.318	13.64	n/a	13.846	16.482	20.558	n/a
C12	16.407	15.228	16.292	6.636	16.752	17.63	18.098	5.192
C13	10.43	11.674	12.128	6.47	17.098	16.292	20.054	4.292
C14	31.55	33.004	28.306	9.526	21.72	23.198	21.524	7.508
C15	41.75	41.084	34.568	1.104	21.15	18.004	18.606	2.886
C16	2.842	3.638	4.794	39.754	5.552	8.156	10.958	55.136
C17	3.344	1.504	1.332	85.68	1.342	2.064	1.934	97.38
C18	15.202	15.24	15.644	6.702	23.396	23.022	22.242	4.736

Table XVI.2: Raw data for fine textured soils

Soil Id		Total Dissolved P (mg L ⁻¹)							
		Run 1				Run 2			
		0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
F1	M 30	0.027	0.026	0.022	0.025	0.017	0.028	0.025	0.017
F2	N 45	0.064	0.041	0.038	0.171	0.106	0.076	0.069	0.229
F3	Fert 1	0.102	0.082	0.073	0.177	0.127	0.081	0.068	0.177
F4	N 34	0.136	0.107	0.112	0.3	0.133	0.102	0.089	0.277
F5	M 34	0.148	0.156	0.151	0.238	0.223	0.204	0.194	0.279
F6	N 136	0.684	0.492	0.49	0.772	0.516	0.447	0.403	0.739
F7	M 29	0.626	0.709	0.506	0.63	0.485	0.449	0.417	1.256
F8	N 39	0.276	0.244	0.221	0.493	0.406	0.357	0.323	0.334
F9	M 27	0.741	0.525	0.439	3.384	0.605	0.485	0.368	3.766
F10	M 35	0.883	0.645	0.321	3.572	0.925	0.641	0.514	3.267
F11	M 41	0.473	0.332	0.261	2.684	0.437	0.337	0.211	2.155
F12	G10E	0.767	0.559	0.464	1.737	0.618	0.642	0.562	1.514
F13	G10W	0.428	0.341	0.284	0.374	0.386	0.367	0.322	0.448
F14	N 40	0.931	0.713	0.684	1.704	0.953	0.853	0.953	2.325
F15	N 37	1.786	0.779	0.684	2.741	0.865	1.334	1.53	2.197
F16	M205	1.104	0.643	0.559	2.352	0.908	0.548	0.607	2.301
F17	G9E	1.184	1.505	1.063	0.993	0.985	0.867	0.877	0.887
F18	M 40	1.032	0.579	0.463	3.918	1.187	0.66	0.675	4.926
F19	G5E	1.454	1.314	1.404	1.993	1.405	1.405	1.57	2.459
F20	M 31	1.153	0.866	0.797	2.621	0.868	0.759	0.674	2.149
F21	M 32	1.074	1.661	1.533	4.334	1.605	1.575	1.605	3.362
F22	G20	3.305	1.916	1.787	7.029	2.813	2.19	6.801	2.102

Soil Id		Particulate P (mg L ⁻¹)							
		Run 1				Run 2			
		0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
F1		10.149	8.999	8.897	0.191	21.81	19.724	23.663	0.401
F2		3.95	2.813	4.193	0.34	2.991	2.203	3.339	0.139
F3		2.706	2.684	3.243	0.251	5.223	3.563	3.753	0.093
F4		3.301	6.432	5.691	0.256	6.454	4.96	9.827	0.124
F5		15.611	13.511	4.336	0.14	16.845	13.167	14.08	0.202
F6		46.634	34.515	33.618	0.576	24.831	19.594	17.701	0.166
F7		15.384	16.959	11.941	0.212	8.292	8.239	8.59	0.379
F8		3.172	1.595	1.981	0.431	12.61	9.992	8.736	0.16
F9		2.222	3.515	6.895	0.672	5.294	4.381	5.091	0.258
F10		9.051	12.208	1.721	0.534	6.381	11.484	9.978	0.388
F11		8.998	7.284	5.181	0.629	2.998	4.592	3.463	0.217
F12		7.4	6.26	7.445	0.388	9.997	9.599	11.175	0.687
F13		10.453	8.288	8.085	1.207	11.537	11.998	7.005	0.454
F14		28.086	17.805	19.616	0.483	37.658	40.661	62.135	0.153
F15		56.887	32.421	44.744	0.758	7.129	7.129	7.051	0.188
F16		28.262	10.447	7.185	0.474	12.269	5.13	11.648	0.449
F17		9.1	27.639	13.024	0.062	13.46	11.611	11.964	0.165
F18		6.35	3.538	7.362	0.528	11.485	6.261	11.884	0.239
F19		13.464	19.069	35.645	2.221	13.128	19.967	35.19	0.451
F20		35.58	22.721	27.008	0.442	20.94	17.108	16.115	0.15
F21		3.236	10.731	14.728	1.28	25.045	23.917	36.885	2.605
F22		36.139	13.618	15.143	1.115	18.564	11.844	0.391	14.317

Soil Id	Total P (mg L ⁻¹)							
	Run 1				Run 2			
	0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
F1	10.176	9.025	8.919	0.216	21.827	19.752	23.688	0.418
F2	4.014	2.854	4.231	0.511	3.097	2.279	3.408	0.368
F3	2.808	2.766	3.316	0.428	5.35	3.644	3.821	0.27
F4	3.437	6.539	5.803	0.556	6.587	5.062	9.916	0.401
F5	15.759	13.667	4.487	0.378	17.068	13.371	14.274	0.481
F6	47.318	35.007	34.108	1.348	25.347	20.041	18.104	0.905
F7	16.01	17.668	12.447	0.842	8.777	8.688	9.007	1.635
F8	3.448	1.839	2.202	0.924	13.016	10.349	9.059	0.494
F9	2.963	4.04	7.334	4.056	5.899	4.866	5.459	4.024
F10	9.934	12.853	2.042	4.106	7.306	12.125	10.492	3.655
F11	9.471	7.616	5.442	3.313	3.435	4.929	3.674	2.372
F12	8.167	6.819	7.909	2.125	10.615	10.241	11.737	2.201
F13	10.881	8.629	8.369	1.581	11.923	12.365	7.327	0.902
F14	29.017	18.518	20.3	2.187	38.611	41.514	63.088	2.478
F15	58.673	33.2	45.428	3.499	7.994	8.463	8.581	2.385
F16	29.366	11.09	7.744	2.826	13.177	5.678	12.255	2.75
F17	10.284	29.144	14.087	1.055	14.445	12.478	12.841	1.052
F18	7.382	4.117	7.825	4.446	12.672	6.921	12.559	5.165
F19	14.918	20.383	37.049	4.214	14.533	21.372	36.76	2.91
F20	36.733	23.587	27.805	3.063	21.808	17.867	16.789	2.299
F21	4.31	12.392	16.261	5.614	26.65	25.492	38.49	5.967
F22	39.444	15.534	16.93	8.144	21.377	14.034	7.192	16.419

Soil Id	Volume (L)							
	Run 1				Run 2			
	0-30	30-60	60-90	Percolate	0-30	30-60	60-90	Percolate
F1	17.059	15.694	16.858	3.162	28.654	34.856	35.262	10.404
F2	10.214	12.196	12.354	9.3	11.462	12.742	13.212	8.636
F3	10.516	15.548	15.46	11.652	12.084	14.744	14.922	11.71
F4	13.833	14	14.182	6.464	11.392	14.624	14.824	11.056
F5	13.186	14.308	13.052	4.008	15.532	16.248	16.758	3.856
F6	17.482	16.966	16.506	2.454	19.47	17.5	17.412	2.976
F7	13.45	13.832	13.968	0.564	31.01	31.804	34.266	2.582
F8	3.964	12.874	15.277	28.53	14.9	17.018	17.562	7.378
F9	9.634	12.872	13.308	10.464	25.057	26.564	23.746	13.756
F10	11.768	14.302	13.076	12.7	10.452	12.682	13.444	8.84
F11	37.388	35.41	38.096	16.816	10.576	16.456	17.694	20.576
F12	13	15.058	15.82	11.68	26.352	26.012	26.688	11.09
F13	17.47	16.68	17.64	6.342	19.448	23.066	25.49	10.524
F14	18.912	18.05	18.866	4.046	18.298	20.308	20.064	5.32
F15	6.587	14.242	16.65	24.746	18.448	22.882	22.316	6.244
F16	22.22	19.268	19.632	2.774	21.04	25.33	25.547	6.824
F17	29.832	30.352	24.602	5.516	15.9	17.46	19.87	8.102
F18	11.104	13.244	13.236	8.578	23.118	28.356	29.646	8.784
F19	17.006	17.962	18.18	12.542	16.998	22.16	23.014	11.386
F20	10.452	12.682	13.144	8.84	15.808	17.226	17.552	3.89
F21	1.146	7.826	12.506	29.734	22.824	31.188	29.304	14.142
F22	15.252	17.414	18.014	7.874	23.328	23.156	27.34	4.826