Forms of P in Different Manures and Their Impact on P Runoff and Leaching Losses from Manure Amended Soils

Final Report Submitted to the

Manitoba Livestock and Manure Management Initiative

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February 2, 2009

EXECUTIVE SUMMARY

Continuous application of manure P above crop removal results in a buildup of soil phosphorus (P), which increases the risk of P runoff loss from agricultural land, leading to environmental problems such as eutrophication of surface waters. There is little or no information about the forms of manure P that are correlated with risk of P loss after manure interacts with soil, especially for prairie soils. The objectives of this study were to quantify and compare P losses from liquid swine- and solid cattle- manure treated soils after incubating for 6 weeks, and to relate P losses to manure P forms and soil test P after incubation.

Amount of P in different fractions of manure samples were quantified using the modified Hedley fractionation. Phosphorus runoff and leaching losses in ten fertility treatments (4 sources of solid cattle manure, 4 sources of liquid swine manure, monoammonium phosphate (MAP) and check) were compared in two soils (Lone Sand and Newdale Clay Loam) with two replicates for each fertility treatment by conducting a rainfall simulation runoff study and a column leaching study. Manure or fertilizer was applied to soil at the rate of 50 mg P kg^{-1} soil (≈100 kg of P ha^{-1}), mixed, moistened to 90% field capacity and incubated at 20 C for 6 weeks. After incubation, treated soils were analyzed for Olsen-P, Mehlich 3-P, Modified Kelowna- P and water extractable P. For the rainfall simulation study, incubated soils were packed into runoff trays and placed at a 5% slope underneath a rainfall simulator providing rainfall at 75 mm h^{-1}intensity. Runoff and percolate samples were collected over a total of 60 minutes and analyzed for soluble reactive P, total dissolved P and total P. For the column leaching study, incubated soils were packed

into PVC columns, and water was supplied through a rain-drip system at a low intensity of 12.5 mm h^{-1}. Leachate samples collected approximately at each 0.25 pore volume up to a total of 4 pore volumes were immediately analyzed for soluble reactive phosphorus. Total dissolved P was determined in four combined samples (volume weighted) for each column.

The total P content on a dry basis was higher in liquid swine manure than in solid cattle manure. Liquid swine manure had a higher proportion of total labile P (total P in water fraction + total P in $NaHCO_3$ fraction) than solid cattle manure. In the runoff study, the SRP concentration in runoff was significantly higher ($p \leq 0.05$) from liquid swine manure and MAP treated soils than from solid cattle manure treated soils. Total runoff SRP load was highest from MAP treated soil followed by liquid swine manure treated soil. The differences between total dissolved P (TDP) and SRP were small, indicating that a very small proportion of dissolved P was in soluble non-reactive P (SNRP) forms. The total P (TP) concentrations in runoff and percolate samples were substantially higher than TDP because of large losses of P as particulate P (PP). Even though the TP and PP losses were higher in this simulated rainfall study, our main focus was on P loss as dissolved P forms, since it has been previously documented that dissolved P forms are the dominant forms of P loss under natural field conditions on the Prairies. Water extractable inorganic P fraction (water-P_i) in manure did not show a significant correlation with P loss in either soil, but the total SRP load (percolate + runoff) during the entire simulation period of 0-60 min was highly correlated ($p \leq 0.001$) with the total P in $NaHCO_3$ fraction ($NaHCO_3$-P_t) and labile P_t (water-P_t + $NaHCO_3$-P_t) fractions in manure. For testing soil, *Mehlich 3, Modified Kelowna and Olsen extractable P were better than water extractable P for predicting SRP loss in runoff, with Olsen P having the highest correlation with runoff SRP loss (r^2=0.49, $p \leq 0.001$).*

In the low intensity leaching study, SRP breakthrough curves in Lone Sand, showed a higher peak concentration with liquid swine manure and MAP treatments than with solid cattle manure and check treatments, but this effect was not observed in the Newdale CL. Total SRP loss during the elution of 3.5 pore volumes of water in Lone Sand was greater than in Newdale CL for the corresponding manure and MAP treatments, even though in the check treatment the amount of SRP loss was similar in the two soils. This implies that the added P in the form of manure or fertilizer is retained more strongly in the Newdale CL. The SRP contributed to more than 95% of the TDP in the volume-weighted combined samples. In Lone Sand, only inorganic P in the NaOH fraction in manure (NaOH-P_i) showed a significant correlation with SRP leaching loss. Water extractable P in soil proved to be the most accurate soil test method to predict SRP loss during low intensity leaching.

The results of this study with replicated sources of liquid swine manure and solid cattle manure revealed that environmental availability of P in liquid swine manure was generally greater than that in solid cattle manure, but less than in MAP. Water-P_i and water-P_t fractions in manure are not good predictors of SRP loss through runoff or leaching once the manure P interacts with soil over 6 weeks of time. Conversely, $NaHCO_3$ - P_t or labile P_t fractions in manure proved to be better predictors of runoff SRP

loss and leaching loss with high intensity rainfall but not of leaching loss with low intensity rainfall over a longer period of time. The equations between SRP loss and labile-P_t fraction in manure were stable for the two soils indicating that the same equation could be used to predict P loss from labile -P_t. Of the four soil test P methods, the Olsen method was best for predicting runoff P loss while water extractable P was best for predicting leaching losses.

GLOSSARY OF TERMS

SRP	Soluble reactive phosphorus, most easily used by algae
SNRP	Soluble non-reactive P, mostly organic forms
TDP	Total dissolved phosphorus, equal to SRP plus SNRP
PP	Particulate phosphorus, P on soil particles that moves by erosion
TP	Total phosphorus, equal to TDP plus PP
STP	Soil test phosphorus, phosphorus extracted by soil testing
P_i	Inorganic forms of phosphorus, not associated with organic matter
P_o	Organic forms of phosphorus, P associated with organic matter
P_t	Total phosphorus, equal to inorganic plus inorganic P
Water-P_i	Inorganic P in water extractable fraction in manure
Water-P_o	Organic P in water extractable fraction in manure
Water-P_t	Total P in water extractable fraction in manure
$NaHCO_3$-P_i	Inorganic P in sodium bicarbonate extractable fraction in manure
$NaHCO_3$-P_o	Organic P in sodium bicarbonate extractable fraction in manure
$NaHCO_3$-P_t	Total P in sodium bicarbonate extractable fraction in manure
NaOH-P_i	Inorganic P in sodium hydroxide extractable fraction in manure
NaOH-P_o	Organic P in sodium hydroxide extractable fraction in manure
NaOH-P_t	Total P in sodium hydroxide extractable fraction in manure
HCl-P_i	Inorganic P in hydrochloric acid extractable fraction in manure
HCl-P_o	Organic P in hydrochloric acid extractable fraction in manure
HCl-P_t	Total P in hydrochloric acid extractable fraction in manure
Labile-P_i	Inorganic P extracted by water + inorganic P extracted by $NaHCO_3$
Labile-P_t	Total P extracted by water + total P extracted by $NaHCO_3$
MAP	Monoammonium phosphate synthetic fertilizer (11-52-0)
CM	Solid Cattle manure
SM	Liquid swine manure
CM1	Solid cattle manure from Forrest, Manitoba
CM2	Solid cattle manure from Lake Francis, Manitoba
CM3	Solid cattle manure from Argyle, Manitoba
CM4	Solid cattle manure from Brandon, Manitoba
SM1	Liquid swine manure from Niverville, Manitoba
SM2	Liquid swine manure from Brunkild, Manitoba
SM3	Liquid swine manure from La Broquerie, Manitoba
SM4	Liquid swine manure from Glenlea, Manitoba
Newdale CL	Newdale Clay Loam
Mehlich 3-P	Soil P extracted by Mehlich 3 method
Modified Kelowna-P	Soil P extracted by modified Kelowna method (e.g., ALS Labs)
Olsen-P	Soil P extracted by Olsen method (e.g., AgVise & Bodycote Labs)
Water-P	Soil P extracted by deionized water

ACKNOWLEDGEMENTS

Authors acknowledge:

The Manitoba Livestock and Manure Management Initiative for financial support

Mulikat Bammeke, Nandakumar Rajendran, Rob Ellis, Clay Sawka, Gordon Finlay and Perry Antifaif for technical help.

Henry Rosing, Ken Crockett, Ryan Boyd, Dr. Kathy Buckley, Scott Dick, Kristian Stephens, Luca Coppi and Clay Sawka for providing the manure samples.

Alberta Agriculture and Rural Development for the loaned rainfall simulator equipment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Continuous application of manure phosphorus (P) in excess of crop removal results in a build up of soil P, increasing the risk of P loss through runoff and leaching, which, in turn, increases the risk of environmental problems such as eutrophication of surface water resources. Eutrophication is a condition that results in an increased growth of algae and aquatic weeds leading to oxygen shortages in water bodies, often controlled by the P concentrations in water. The main processes that move P into water bodies and increase the risk of eutrophication are runoff of particulate and dissolved P directly into surface water and leaching of P into groundwater, where the P can re-emerge into surface water. P runoff, traditionally regarded as the most common pathway of water contamination from agricultural land, dominates on medium and fine textured soils where rates of infiltration are slow and water holding capacity is high. The environmental threat from this type of P loss is revealed quickly and can be remediated reasonably quickly, as well. Phosphorus leaching has received very little attention in the past due to the erroneous assumption that P was held so strongly by the soil that it was not leached. One of the first studies to demonstrate the capacity for P to leach was conducted on cattle feedlot sites in Manitoba (Campbell and Racz 1975). Recent studies in Quebec, the Eastern U.S., England and the Netherlands have also shown that high concentrations of P in soil, especially in the form of organic P, create the potential for leaching of environmentally significant quantities of P into groundwater (Brookes et al. 1997, Hesketh and Brookes 2000, Schoumans and Groenendijk 2000, Simard et al. 2000, Sims et al. 1998). Some of these studies, for example, have shown substantial leaching losses at 60 mg kg^{-1} of Olsen P, one-half the upper threshold currently used in Manitoba's manure P regulations (Hesketh and Brookes 2000). The risk posed by P leaching is greatest in coarse-textured soils, clay soils that crack upon drying and tile-drained soils. Also, unlike runoff P losses, this pathway of P contamination does not reveal itself in the short term, but poses a long term threat to surface water quality and is extremely difficult to correct within a reasonable time period.

The risk of leaching and runoff losses of P is more related to the form of P than the total P present in manure (Sharpley and Moyer, 2000). Both the total P and the amount of P in different fractions vary widely among different manure types (Ajiboye et al., 2004). For example, the total P content in hog manure was found to be more than 10 times greater than dairy cattle manure and beef cattle manure, while the water extractable P as a % of total P was greater in hog manure as well (Ajiboye et al., 2004). Dairy cattle manure, on the other hand, consists of a higher proportion 0.5 M sodium bicarbonate and 0.1 M NaOH extractable P than beef cattle manure and hog manure (Ajiboye et al., 2004). Water extractable P in manure has been found to be a good indicator of P runoff loss with dairy cow manure, poultry manure and swine slurry freshly applied to Pennsylvania soils (Kleinman et al., 2005). However, more information is needed about how different P fractions in manure are related to P loss by runoff and leaching several weeks after application, especially for Manitoba's situation where much of the manure is applied in fall and much of the runoff occurs in during spring snowmelt. In the above context, this study was conducted to (a) quantify and compare P runoff and leaching losses from liquid swine manure-, solid cattle manure- and synthetic fertilizer (MAP)- treated sandy soil and clay soil after incubating for 6 weeks; and (b) relate P losses to manure P fractions and soil test P after incubation.

2. MATERIALS AND METHODS

2.1. Collection of manure and soil samples

Representative samples of liquid swine and solid beef cattle manure were collected from various commercial livestock operations within Manitoba. For each manure type, samples were collected from four different sources. Solid beef cattle manure samples were collected from farms near Forrest (CM1), Lake Francis (CM2), Argyle (CM3), and Brandon (CM4). Liquid swine manure samples were collected from hog operations near Niverville (SM1), Brunkild (SM2), La Broquerie (SM3) and Glenlea (SM4). Samples were collected in plastic buckets, mixed and stored in a freezer until used

Soil from surface horizons (0-15 cm) of a Newdale Clay Loam was collected from western Manitoba (Brandon) and soil from surface horizons of a Lone Sand was collected from La Broquerie, Manitoba in fall of 2006. Soil samples were analysed for soil texture, pH, cation exchange capacity, organic matter %, carbonate %, Olsen P, exchangeable Ca and Mg, field capacity and field moisture content.

2.2 Manure analysis

Manure samples were analyzed for total phosphorus using 4 subsamples (initial analysis). Another 4 subsamples of manure were taken during application to soil for sequential fractionation using the modified Hedley fractionation procedure to quantify the P in different fractions (Akinremi et al. 2003). Subsamples of each manure sample were sequentially extracted with de-ionized water, 0.5 M $NaHCO_3$, 0.1 M NaOH, and 1 M HCl. For the first extraction with de-ionized water, 0.3-g (oven dry basis) of manure sample was weighed into a 50 mL centrifuge tube along with 30 mL of de-ionized water and shaken for 16 h at room temperature on an end-to-end shaker at 150 excursions per minute. The sample was centrifuged at 10,000 g for 15 min and vacuum-filtered using a 0.45-µm cellulose membrane. The residue was extracted using 30 mL of each successive extractant. Inorganic P (P_i) in the extracts was determined colorimetrically by the molybdate-blue method (Murphy and Riley, 1962) using a UV/visible spectrophotometer at a wavelength of 882 nm. Total P (P_t) in each extract was analysed using ICP-AS. The organic P (P_o) in each extract was estimated as the difference between total P and inorganic P. Residual P was determined using the sulphuric acid-hydrogen peroxide digestion (Akinremi et al., 2003) of the residue remaining after all the extraction steps and analyzed colorimetrically using the molybdate-blue method. Total P of manure from the sequential fractionation procedure was calculated as the sum of P_t in each fraction and the residual P. Water soluble P along with $NaHCO_3$ P_i and P_o are generally considered as labile P forms while the NaOH extractable Pi and Po are considered as moderately labile. In this study, residual P is considered as the recalcitrant forms of P.

2.3. Manure and fertilizer treatments

In both the rainfall simulation and column leaching experiments, phosphorus losses in the ten fertility treatments were quantified and compared in the two soils (Newdale CL and Lone Sand) with two replicates for each treatment, using a completely randomized design. The fertility treatments were:

- Soil amended with liquid swine manure from 4 sources – SM1, SM2, SM3, SM4
- Soil amended with solid cattle manure from 4 sources – CM1, CM2, CM3, CM4

- Soil amended with synthetic P fertilizer (monoammonium phosphate) - MAP
- Unamended soil – Check

Different manures and MAP were applied to each surface soil at the rate of 50 mg kg^{-1} soils (equivalent to approximately 100 kg of P ha^{-1} to a 15 cm depth) and thoroughly mixed with the soil. The amount of manure to be added was based on the initial analysis of total P.

Soils were sieved using a 10 mm mesh sieve prior to manure or fertilizer treatment. Treated soils of each replicate were mixed, moistened to 90 % field capacity and incubated for a period of 6 weeks at 20 C. Prior to the runoff and leaching experiments, the amended soils were pre-wetted from the bottom by capillary rise. After incubation and prior to leaching and runoff, subsamples from the amended soils were air dried, ground, sieved (2 mm mesh) and analysed for Olsen P (Olsen et al., 1954), Modified Kelowna P (modified Kelowna; Ashworth and Mrazek, 1989; 1995), Mehlich 3 P (Mehlich, 1994) and water extractable P (Kuo, 1996).

2.4. Rainfall simulation study

Amended soils after incubation were packed into runoff trays of 0.90 m wide and 0.2 m long to a depth of 0.1 m. The trays consisted of two compartments, an upper compartment where the soil was packed and a lower compartment to allow pre-wetting of the packed soils through capillary rise and to collect the percolate. Amended soils from Lone Sand and Newdale CL were packed to a bulk density of 1.2 and 1.1 g cm^{-3}, respectively. After 18 h of pre-wetting, packed soil was allowed to drain by gravity for

60 min, after which one side of the runoff tray was raised to a slope of 5 %. A slope of 5% is the most frequently used in the literature for laboratory rainfall simulations (Sharpley, 1995) and will ensure sufficient runoff. Runoff trays (two at a time) were placed underneath a rainfall simulator constructed according to the design by Humphry (2002) and operated according to practices used by Wright et al. (2006) in studies with Alberta soils. The spray nozzle was operated at 28 kPa, 3 m above the trays, delivering 214 mL s^{-1} or a rate of 75 mm h^{-1}. Seventy five mm h^{-1} for 30 min represents a one in 50 year storm event in the prairies. Runoff water as well as water percolating through the runoff trays were collected using a vacuum pump. Runoff samples were collected at 30 min intervals while the simulation was run for a total period of 60 min (i.e. samples were collected for 0-30 min and 30-60 min). The percolate, too, was collected into a single bulk sample and sub-sampled after 60 min Total runoff and percolate volumes were measured. Sediment loss was determined by evaporating a subsample of runoff water.

Runoff and percolate samples were analyzed within 24 h for soluble reactive P (SRP). For the analysis of soluble reactive P, the collected samples were vacuum-filtered using a 0.45-μm cellulose membrane (Torbert et al. 2002; Kleinman et al. 2002) and P in the filtrate was analyzed colorimetrically using the molybdate-blue method (Murphy and Riley, 1962) using a UV/visible spectrophotometer at a wavelength of 882 nm. Total dissolved P in samples was analyzed by ICP-AS and the soluble non-reactive P (SNRP) was calculated as the difference between TDP and SRP. Total P (TP) in runoff and percolate samples was determined by measuring the P content in sulphuric acid-hydrogen peroxide digests of runoff and percolate subsamples. Particulate P (PP) was calculated as the difference between the total P and the total dissolved P. Runoff and percolate losses of P in terms of mg L^{-1} and mg $tray^{-1}$, and the losses as a % of the amount of P added were calculated for each replicate.

2.5. Column leaching study

A leaching study was conducted using soil columns in PVC pipes (10 cm i.d., 15 cm length). A perforated PVC disk of 10 cm diameter with approximately 15 evenly spaced, 0.2 cm perforations was glued to the bottom end of the column. Columns were packed to a bulk density of 1.2 g cm^{-3} with Lone Sand and to a bulk density of 1.1 g cm^{-3} with Newdale CL to a length of 15 cm from the base. Soil columns were saturated from the bottom using de-ionized water for 18 h and left to drain by gravity for 1 h.

Columns were placed under a rain-drip watering system, consisting of an air-tight acrylic reservoir filled with de-ionized water having capillary drip tubes at the bottom end, and an adjustable bubbling tube to control the pressure head as described by Mersie et al. (1999). By adjusting the bubbling tube, the flux rate was adjusted to deliver simulated rainfall at a rate of 12.5 mm h^{-1}. Soil columns were connected to a suction pump from the bottom end to extract leachate samples at a rate of 12.5 mm h^{-1}, so that influx was equal to outflux. Sub samples of the leachate were drawn into a fraction collector at intervals of approximately 0.25 pore volume until a total of approximately 4 pore volumes of water had leached through the column. Volume of each leachate sample was recorded and a subsample was analyzed within 24 h for soluble reactive P using the same procedures as for the runoff study. Total dissolved P was determined using ICP-AS and the soluble non-reactive P (SNRP) was calculated as the difference between TDP and SRP. Leaching losses of P in each replicate were calculated as mg L^{-1}, mg $tray^{-1}$ and the % of P added.

2.6. Statistical analysis

Analysis of variance (ANOVA) of runoff and percolate P loss data was performed using the MIXED procedure in SAS version 9.1 (SAS Institute Inc. 2007) with mean separation by Tukey-Kramer Test. Analysis of variance was performed considering different sources of each manure type as replicates (four fertility treatments; two manure treatments with eight replicates each and MAP and check treatments with two replicates each). Analysis of Variance was conducted with natural log transformed data whenever untransformed data did not follow a normal distribution. Relationships between the runoff and leaching loss of P in different fertility treatments with soil test P after incubation, and with manure P forms were quantified by least squares regression, and differences in slopes of regression equations were assessed by a homogeneity of regression test (Steel and Torrie, 1980). All correlation and regression analyses except homogeneity of regression tests were carried out with the Data Analysis tool pack in Microsoft Excel 2003 (Microsoft, Seattle, Washington) software package. For all statistical analyses, significance was set at $p \leq 0.05$.

3. RESULTS AND DISCUSSION

3.1. Soil properties

The two soils used in the study showed contrasting physical and chemical properties. Texturally, the Newdale soil was a sandy clay loam while the Lone Sand was of sand textural class. Soil pH values were similar in the two soils, with slightly higher pH of 6.5 in Newdale CL compared to 6.1 in Lone Sand. Cation exchange capacity, organic matter % and exchangeable Ca and Mg concentrations were much higher in Newdale CL than Lone Sand because of the higher clay content in the Newdale CL. Initial Olsen P concentration was 29.8 mg kg^{-1} in Newdale CL and 19.6 mg kg^{-1} in Lone Sand (Table 1).

3.2. Solid content and total P in manure

The percent solid content ranged from 3.5 to 6.7, and 20.4 to 49.0 in liquid swine manure and solid cattle manure, respectively (Table 2). The average solid content of 33.7% in solid cattle manure was significantly ($p\leq 0.001$) higher than 5.2 % in liquid swine manure. Based on the initial analysis, the total P content on a wet basis in two types of manure was similar with an average of 1.2 and 1.7 kg t^{-1} in liquid swine manure and solid cattle manure, respectively. Variation in total P content among sub samples was greater in solid cattle manure than in liquid swine manure. A considerable variation was also seen between total P in the initial analysis and the total P calculated from sequential extraction of samples collected during manure application. The estimated quantity of manure P added varied in treatments, but the variation was slight in liquid swine manure than in solid cattle manure. The estimated total P added based on sequential fractionation results was 44.5 ± 2.1 and 50.1 ± 18.2 mg kg^{-1} soil in liquid swine manure and solid cattle manure treatments, respectively, while the MAP treatment received 50 mg of P kg^{-1} soil.

3.3. Forms of P in manure

Inorganic P (P_i) content in different fractions varied between the type of manure as well as among different sources of the same type of manure. In general, water soluble inorganic P fraction (water-P_i) was higher in liquid swine manure than solid cattle manure, except for SM2, which had a comparatively low water- P_i fraction (Table 3). For liquid swine manure, the average water-P_i fraction was 3.42 kg t^{-1} on a dry basis, which is significantly higher than the corresponding water-P_i fraction of 0.8 kg t^{-1} in solid cattle manure (Table 3). Inorganic P concentrations in $NaHCO_3$, NaOH and HCl extractable fractions were significantly higher in liquid swine manure than solid cattle manure. Thus, the total inorganic P (sum of P_i in all fractions) in liquid swine manure on a dry weight basis was more than 5-fold (15.39 kg t^{-1}) of that in solid cattle manure (3.12 kg t^{-1}).

A similar trend was observed with the total P content (P_t) in different fractions (Table 4). Liquid swine manure had significantly higher P_t in water, $NaHCO_3$, NaOH and HCl extractable fractions than solid cattle manure. The residual P content (the amount of P that was not extracted by all the above extractants) was greater in solid cattle manure than in liquid swine manure. Thus, the labile P fraction was significantly higher in liquid swine manure compared to solid cattle manure. Solid cattle manure on the other hand, had significantly more recalcitrant P than liquid swine manure.

The difference between P_t and P_i was not large, indicating that approximately 75% and 60% of P in these fractions in liquid swine and solid cattle manure, respectively, was in inorganic form. The proportion of inorganic P varied in different fractions (Table 5). More than 70% of P was in inorganic form in water, $NaHCO_3$ and HCl extractable fractions, in both liquid swine manure and solid cattle manure. However, the proportion of inorganic P in the NaOH extractable fraction was lower, with 62 and 24%, for liquid swine manure and solid cattle manure, respectively. Thus, the NaOH fraction had a higher proportion of organic P compared to other fractions in both liquid swine and solid cattle manure. The proportion of organic P in the water extractable fraction was significantly ($p \leq 0.05$) higher in liquid swine manure than solid cattle manure whereas the proportion of organic P in NaOH fraction was significantly higher ($p \leq 0.01$) in solid cattle manure than in liquid swine manure. Thus the organic P in solid cattle manure was less labile than in liquid swine manure.

When expressed as a percentage of total P, the amount of labile P (P in water soluble and $NaHCO_3$ extractable fractions) in liquid swine manure ranged between 50-80% of total P (Figure 1). In contrast, % labile P in solid cattle manure ranged between 40-50% of total P, indicating that more than 50% of the P in solid cattle manure was in less labile and recalcitrant forms (Figure 1). The residual P content was very low in liquid swine manure, less than 5 % of the total P, whereas in solid cattle manure, more than 20% of the P was found in the residual P fraction. In summary, liquid swine manure had higher total P content on a dry weight basis, with higher percent of P in labile forms. In contrast, solid cattle manure had lower total P content, with less proportion of P in labile forms and more in recalcitrant forms.

Table 1. Important physical and chemical properties of the two soils

Soil property	**Newdale CL**	**Lone Sand**
pH (1:2.5 soil: water)	6.5	6.1
Cation exchange capacity (cmol kg^{-1})	26.8	6.6
Organic matter (%)	5.7	1.3
Carbonate (%)	0.1	0.0
Olsen P (mg kg^{-1})	29.8	19.6
Exchangeable Ca (cmol kg^{-1})	9.0	2.5
Exchangeable Mg (cmol kg^{-1})	3.9	0.6
Field capacity (w/w %)	43	17
Sand %	52	96
Silt %	22	2
Clay %	26	2
Textural class	Sandy clay loam	Sand

Table 2. Solid content, total P in different types and sources of manure and estimated P added in different treatments

Type/source of manure	Solid content (%)	Total P on a wet basis[1]		Estimated amount[2] of total P added (mg kg^{-1} soil)
		Initial analysis[3]	Sequential extraction[4]	
Liquid swine manures		**(kg 1000 L^{-1})**	**(kg 1000 L^{-1})**	
SM1	6.3	1.3 ± 0.02	1.15 ± 0.02	45.37
SM2	3.5	0.7 ± 0.03	0.66 ± 0.06	46.62
SM3	4.5	0.9 ± 0.02	0.75 ± 0.03	41.81
SM4	6.7	2.0 ± 0.18	1.78 ± 0.05	44.35
Mean[5]	**5.2 b**	**1.2 a**	**1.08 a**	**44.5**
SD	**1.4**	**0.6**	**0.62**	**2.1**
Solid cattle manures		**(kg t^{-1})**	**(kg t^{-1})**	
CM1	41.9	1.4 ± 0.17	1.3 ± 0.09	47.64
CM2	49.0	2.2 ± 0.66	2.3 ± 0.14	51.12
CM3	23.7	1.7 ± 0.18	2.1 ± 0.18	74.38
CM4	20.4	1.7 ± 0.16	0.97 ± 0.07	30.04
Mean[5]	**33.7 a**	**1.7 a**	**1.67 b**	**50.8**
SD	**13.8**	**0.4**	**0.71**	**18.2**

[1] Average of four replicate samples for each manure source
[2] Estimated amounts added based on the total P calculated from sequential extraction at application. MAP treatment received 50 mg P per kg soil.
[3] Initial analyses of subsamples for total P prior to manure application
[4] Total P calculated from sequential fractionation results of subsamples collected during manure application
[5] Mean values (mean of four sources) within the same column followed by the same lower case letter are not significantly different at $p \leq 0.05$.

Table 3. Inorganic P (P_i) content in different fractions in manures

Type/source of manure	Inorganic P (P_i) in different fractions on dry weight basis (kg t^{-1})				
	Water-P_i	**$NaHCO_3$ - P_i**	**NaOH - P_i**	**HCl - P_i**	**Total- P_i**
Liquid swine manures					
SM1	2.73	11.79	1.64	0.94	17.09
SM2	0.69	6.76	3.32	2.43	13.20
SM3	2.63	5.21	1.66	0.62	10.12
SM4	7.63	8.19	1.80	3.52	21.14
Mean[1]	**3.42 a**	**7.99 a**	**2.10 a**	**1.88 a**	**15.39 a**
Solid cattle manures					
CM1	0.47	0.63	0.11	0.38	1.59
CM2	0.78	1.14	0.17	1.10	3.20
CM3	1.21	3.15	0.46	0.83	5.66
CM4	0.72	0.82	0.07	0.41	2.02
Mean[1]	**0.80 b**	**1.44 b**	**0.20 b**	**0.68 a**	**3.12 b**

[1] Mean values (mean of four sources) within the same column followed by the same lower case letter are not significantly different at $p \le 0.05$.

Table 4. Total P (P_t) content in different fractions in manures

Type/source of manure	Total P (P_t) in different fractions on dry weight basis (kg t^{-1})					
	Water-P_t	$NaHCO_3$ -P_t	NaOH - P_t	HCl- P_t	Residual-P_t	Total- P_t
Liquid swine manures						
SM1	3.74	10.96	2.05	1.10	0.43	18.28
SM2	0.90	8.07	6.65	2.50	0.67	18.79
SM3	3.12	9.95	2.27	0.90	0.44	16.68
SM4	9.23	10.05	2.57	4.29	0.52	26.65
Mean[1]	**4.25 a**	**9.76 a**	**3.39 a**	**2.20 a**	**0.51 b**	**20.10 a**
Solid cattle manures						
CM1	0.53	0.66	0.58	0.52	0.81	3.10
CM2	0.86	1.12	0.55	1.17	0.95	4.64
CM3	1.32	3.15	1.43	1.23	1.80	8.92
CM4	0.87	0.88	0.79	0.79	1.28	4.62
Mean[1]	**0.89 b**	**1.45 b**	**0.84 b**	**0.93 b**	**1.21 a**	**5.32 b**

[1] Mean values (mean of four sources) within the same column followed by the same lower case letter are not significantly different at $p \le 0.05$.

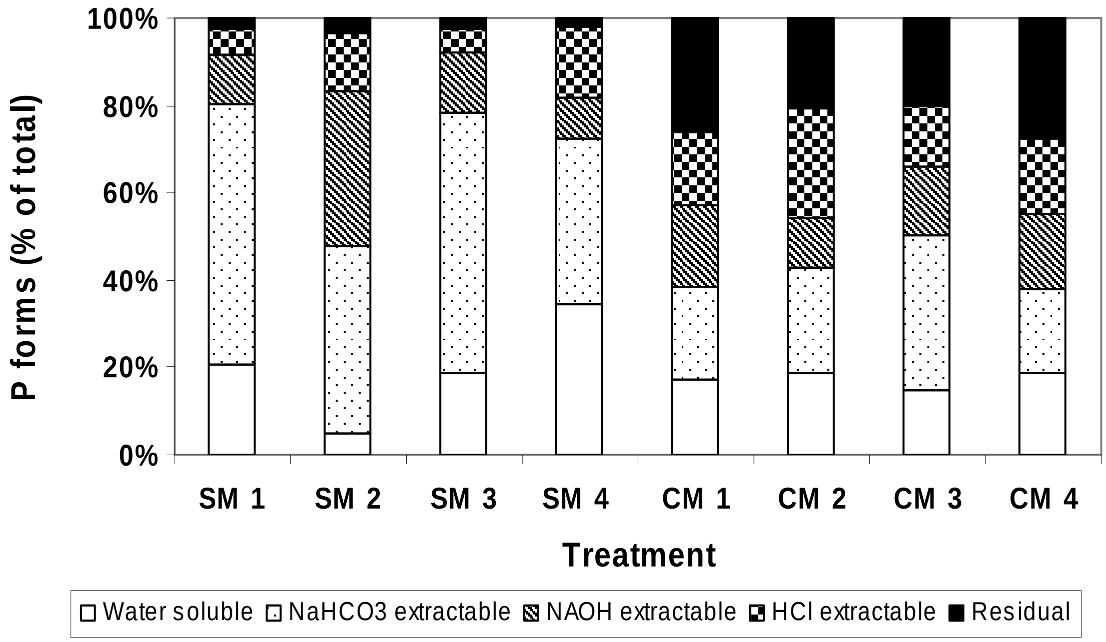


Figure 1. **Forms of P as a percentage of total P in different types and sources of manure**

Table 5. Proportion of inorganic and organic P in different fractions in manures

Type/source of manure	Percent inorganic (P_i) and organic P (P_o) in different fractions							
	Water		$NaHCO_3$		NaOH		HCl	
	P_i	P_o	P_i	P_o	P_i	P_o	P_i	P_o
Liquid swine manures								
SM1	72.9	27.1	98.4	1.6	79.7	20.3	85.4	14.6
SM2	77.2	22.8	83.8	16.2	49.8	50.2	97.3	2.7
SM3	84.3	15.8	52.4	47.6	73.1	26.9	68.9	31.1
SM4	82.7	17.3	81.5	18.5	70.1	29.9	82.2	17.8
Mean[1]	**80.5 b**	**19.5 a**	**79.3 a**	**20.7 a**	**62.1 a**	**37.9 b**	**85.5 a**	**14.5 a**
Solid cattle manures								
CM1	88.4	11.6	94.9	5.1	18.6	81.4	73.5	26.5
CM2	90.7	9.3	99.4	0.6	31.6	68.4	94.4	5.6
CM3	92.2	7.8	99.8	0.2	32.5	67.5	67.9	32.1
CM4	82.6	17.4	92.8	7.3	8.8	91.2	51.9	48.1
Mean[1]	**88.9 a**	**11.1 b**	**98.1 a**	**1.9 a**	**24.4 b**	**75.7 a**	**73.6 a**	**26.4 a**

[1] Mean values (mean of four sources) within the same column followed by the same lower case letter are not significantly different at $p \leq 0.05$.

3.4. Runoff simulation study

3.4.1. Runoff and percolate volumes

Volumes of runoff samples collected at both 0-30 and 30-60 min periods were greater in Newdale CL that in Lone Sand (Appendix 1). The average total (0-60 min) runoff volume over all fertility treatments and replicates was 31.0 L for Newdale CL and 26.5 L for Lone Sand. This difference was mainly due to the differences in texture and infiltration rates between the two soils. The percolate volumes on the other hand were higher in the Lone Sand than the Newdale CL (Appendix 1), averaging 0.64 and 2.79 L for Newdale CL and Lone Sand, respectively.

3.4.2. Sediment loss

Sediment loss with runoff was significantly higher in the Newdale CL than Lone Sand (Appendix 2), since the Newdale CL had a higher proportion of fine particles which are more prone to runoff losses. The average total sediment loss from 0-60 min runoff was 428 g $tray^{-1}$ in the Newdale CL compared to 54 g $tray^{-1}$ in the Lone Sand. Since P is often bound to finer clay particles, high sediment loss may contribute to high losses of P as particulate P with runoff water.

3.4.3. Runoff and percolate SRP concentrations and loads

Soluble reactive P concentrations in runoff samples varied among fertility treatments (Figure 2 and Appendix 3). The fertility treatment effect was highly significant for 0-30 min runoff SRP concentrations (Table 6). In Lone Sand, SRP concentrations in 0-30 min runoff samples were numerically higher than in Newdale CL in most fertility treatments (Figure 2a) but this difference was not significant. Runoff SRP concentrations at 0-30 min were significantly higher from liquid swine manure and MAP treated soils than from solid cattle manure treated and unamended (check treatment) soils (Table 6).

Runoff SRP concentrations at 30-60 min showed a similar trend among the manure treatments (Figure 2b). Main and interaction effects of soil and fertility treatment were significant. Liquid swine manure treatments produced higher SRP concentration than solid cattle manure treatment in both soils but the differences were not statistically significant (Table 6). When the two soils are compared, 30-60 min runoff SRP concentrations were higher in Newdale CL than in Lone Sand in all the fertility treatments (Figure 2b) in contrast to 0-30 min runoff SRP concentrations. The reason for the lower SRP concentrations in Newdale CL at 0-30 min. and higher SRP concentrations at 30-60 min when compared to corresponding SRP concentrations in Lone Sand could be the higher buffering ability of the Newdale CL, which releases P slowly over time, whereas, in the Lone Sand, which is poorly buffered, P release was more rapid.

The fertility treatment effect was highly significant for runoff SRP load during the entire simulation period (Table 6). Runoff SRP load was significantly higher from Newdale CL than Lone Sand (Table 6 and Figure 3a). The highest SRP load from runoff during the entire simulation period of 60 min was observed from MAP treated soils, followed by liquid swine manure treated soils (Table 6 and Appendix 4). Thus, broadcasting synthetic P fertilizers onto fine textured soils where runoff losses are high may result in large losses of P to surface water. The difference in SRP runoff load between MAP and solid cattle manure treated soils was significant while the differences between MAP and liquid swine manure treated soils and the differences between liquid swine manure and solid cattle manure treated soils were not significant. Manure or MAP amended soils had significantly greater runoff SRP load than the check (unamended) treatment (Table 6).

The amount of SRP loss with percolate expressed as load was negligible in the Newdale CL (Figure 3b, Table 6) as the percolate volume itself was low. However, in the Lone Sand, percolate loss of SRP was significantly greater and contributed to a substantial proportion of the total SRP loss. Main and interaction effects of soil and fertility treatment were significant for the percolate SRP loss (Table 6). Percolate loss of SRP from Newdale CL was significantly lower than from Lone Sand. However, in Lone Sand, the percolate loss from liquid swine manure treated soil was significantly greater than from solid cattle manure and MAP treated soils while in Newdale CL, the difference in percolate SRP loss among fertility treatments was not significant.

In both soils, SRP removed with runoff as a % of P added was higher from liquid swine manure treated soils than from solid cattle manure treated soils. Loss of SRP with runoff as a % of P added in Lone Sand was 0.92 and 0.52 % from liquid swine manure- and solid cattle manure- treated soils, respectively (Figure 4). Corresponding P losses in the Newdale CL were higher than in Lone Sand with losses of 1.25 and 0.99%, from liquid swine manure- and solid cattle manure- treated soils, respectively. In Lone Sand, SRP removed with percolate was greater in liquid swine manure treatments compared to solid cattle manure treatments and contributed approximately 50% of the total P removed. However, SRP loss with percolate as a % of P added was negligible in Newdale CL.

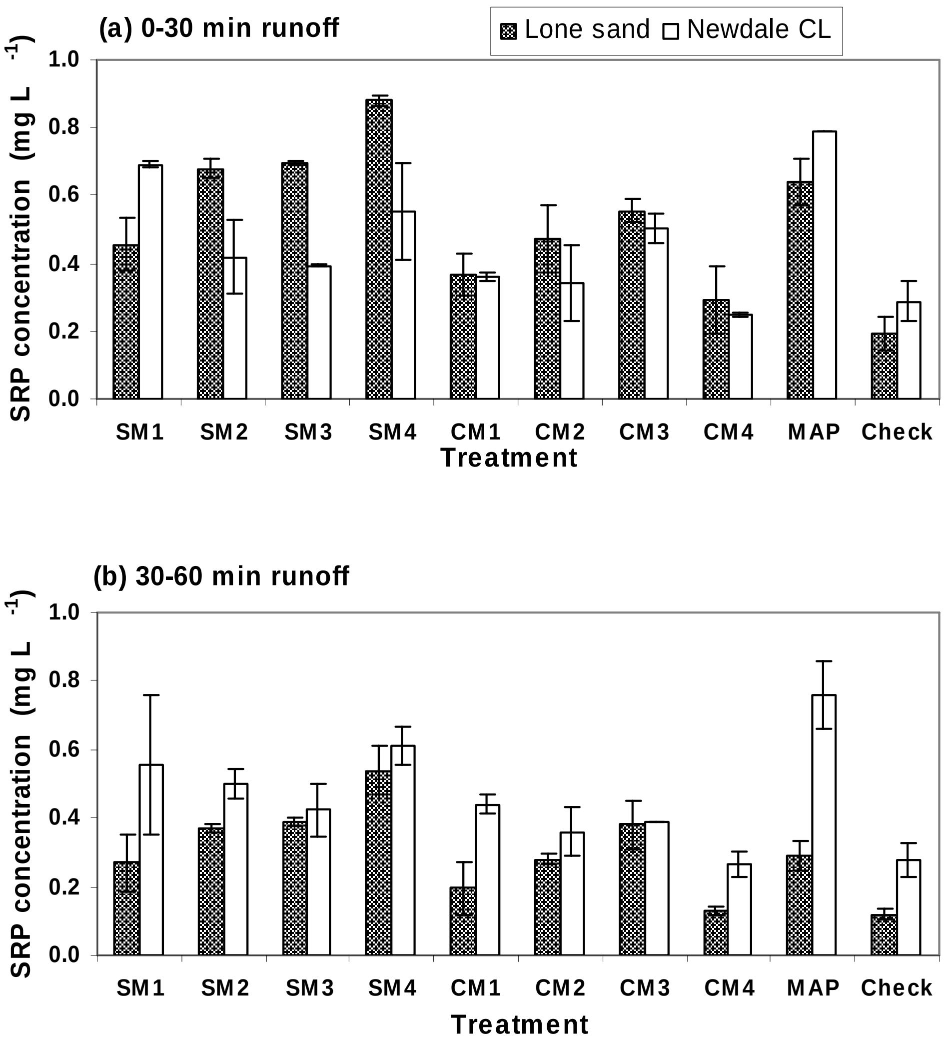


Figure 2. **SRP concentration in runoff samples from different fertility treatments in Lone Sand and Newdale CL (a) 0-30 min runoff (b) 30-60 min runoff**

Table 6. Least square means[1] of runoff SRP concentration, and runoff and percolate SRP loads in different fertility treatments

Effect	Runoff SRP[2] conc'n. (mg L^{-1})		Runoff SRP load[2](mg tray^{-1})	Percolate SRP load[2] (mg tray^{-1})
	0-30 min	**30-60 min**	**0-60 min**	**0-60 min**
Soil				
Lone Sand	0.49		9.76 b	
Newdale CL	0.48		14.39 a	
Fertility treatment				
Liquid swine manure	0.60 a		13.96 ab	
Solid cattle manure	0.39 b		11.01 b	
MAP	0.71 a		18.12 a	
Check	0.24 b		5.21 c	
Soil x Fertility Treatment				
Lone Sand				
Liquid swine manure		0.39 a		10.34 a
Solid cattle manure		0.25 ab		4.93 b
MAP		0.29 ab		1.82 b
Check		0.12 b		0.13 b
Newdale CL				
Liquid swine manure		0.52 ab		0.58 a
Solid cattle manure		0.36 b		0.48 a
MAP		0.76 a		0.29 a
Check		0.27 b		0.23 a
ANOVA			**P>F**	
Soil	**0.9098**	**<0.0001**	**0.0195**	**0.0054**
Fertility treatment	**<0.0001**	**<0.0001**	**0.0001**	**<0.0001**
Soil x Fert. Treatment	**0.1077**	**0.0216**	**0.0662**	**0.0001**

[1] LS Mean values computed using Proc Mixed (SAS version 9.1) for two way ANOVA considering different sources of manure as replicates; 2 soils, 4 fertility treatments (8 replicates for fertility treatments 1 and 2; 2 replicates for fertility treatments 3 and 4).

[2] LS means within the same column followed by the same lower case letter are not significantly different at p≤0.05 by Tukey-Kramer test. Mean separation for main effects presented only in the absence of significant (p≤0.05) interaction effects.

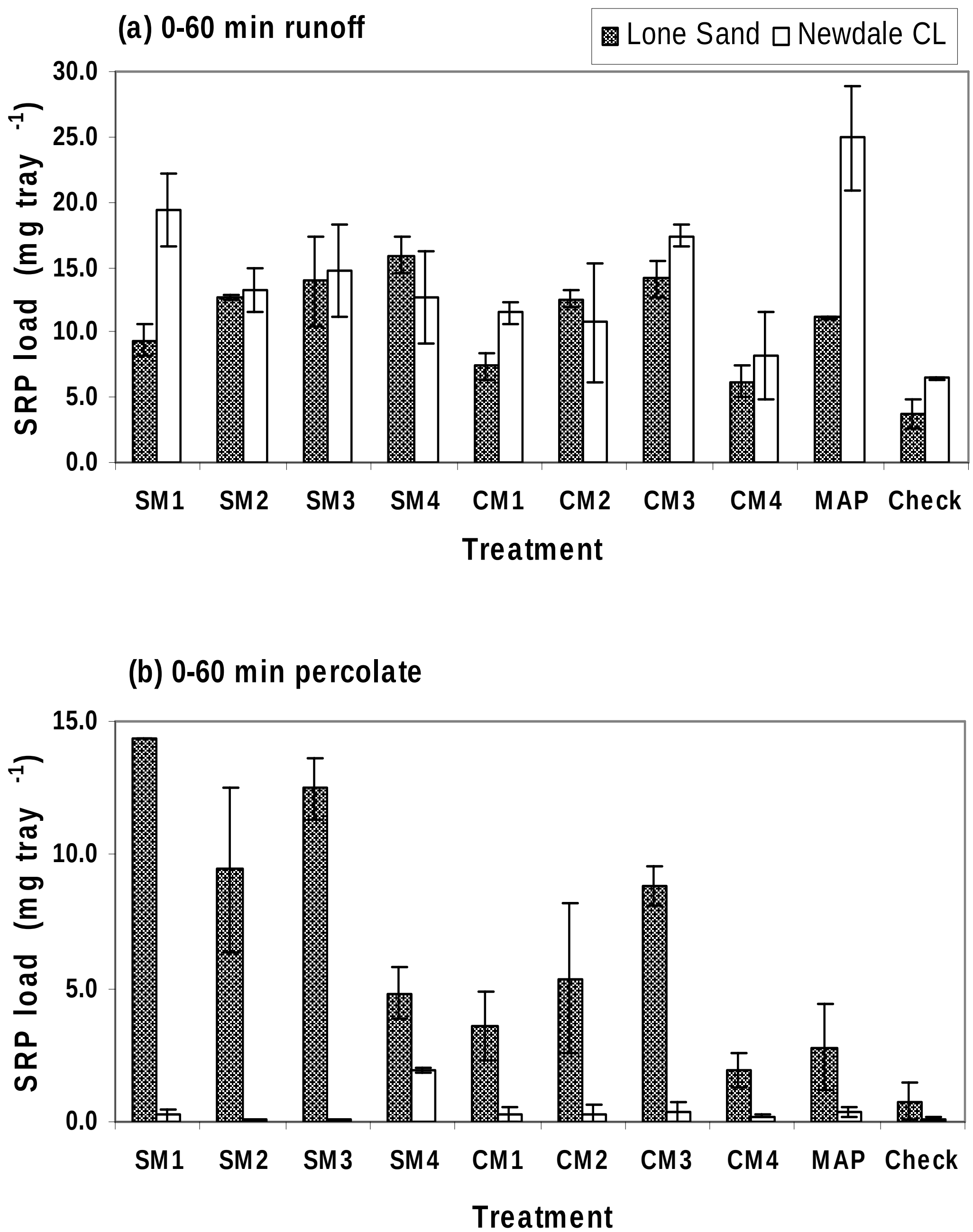


Figure 3. **Runoff and percolate SRP load from different fertility treatments in Lone Sand and Newdale CL (a) 0-60 min runoff (b) 0-60 min percolate**

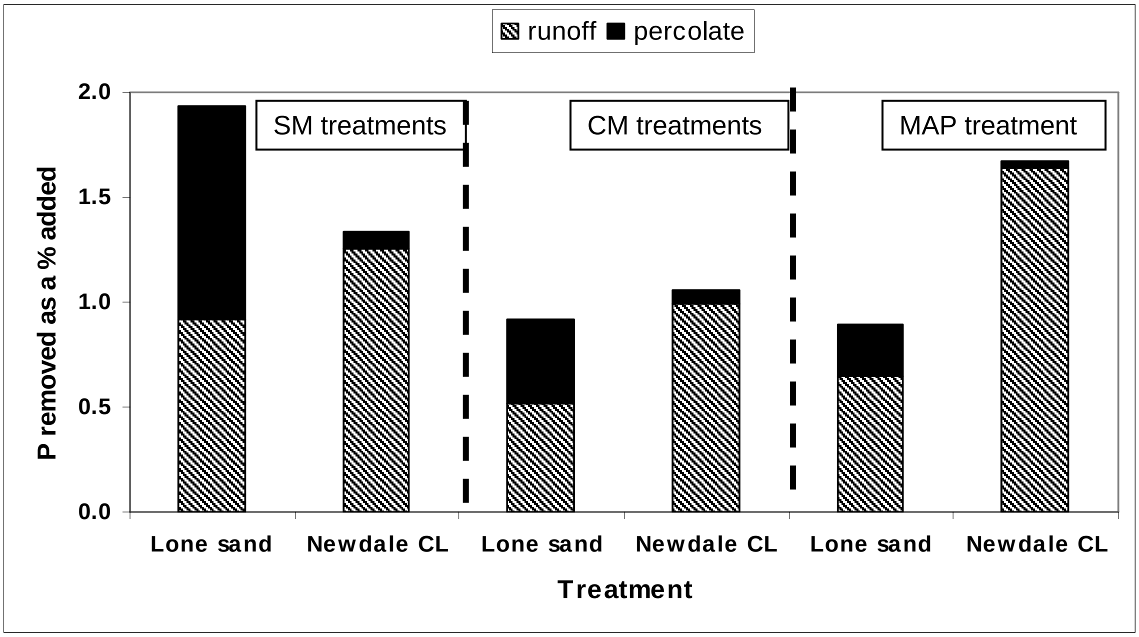


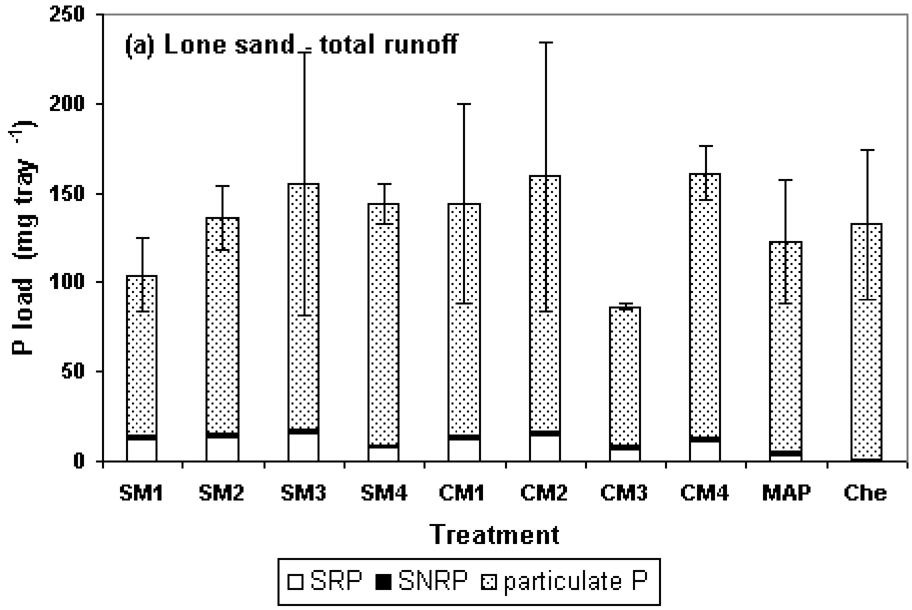
Figure 4. P removed with runoff and percolate as a percentage of added P in manure (average of four sources) and MAP treatments in Lone Sand and Newdale CL

3.4.4. Runoff and percolate TDP, TP and PP concentrations and loads

The differences between total dissolved phosphorus (TDP) concentrations and soluble reactive P (SRP) concentrations in runoff and percolate samples were small (Appendix 3 and 5). When converted to loads, the SRP load contributed to more than 94% of TDP loads (Appendix 4 and 6) indicating that less than 6% was in soluble non-reactive forms of P (Figure 5 and 6). Total P (TP) concentrations and loads in both 0-30 and 30-60 min runoff samples were higher in Newdale CL than in Lone Sand for all fertility treatments (Appendix 7 and 8). This is due to the greater loss of particulate P with runoff in Newdale CL since runoff water carried greater amounts of sediments in Newdale CL than in Lone Sand (Appendix 2). Percolate TP concentrations and loads were, however, greater in Lone Sand than in Newdale CL (Appendix 7 and 8). The main effect of soil was significant for runoff TP and PP loads while the effect of the fertility treatment x interaction was not significant (Table 7). Both TP and PP loads with runoff were significantly higher in Newdale CL than in Lone Sand (Table 7). For TP and PP loads with percolate loss, both main and interaction effects were not significant.

Particulate P load contributed to an average of 94% of total P load in runoff samples whereas in percolate samples, the contribution of PP to TP was about 54% on average. Even though in this study with simulated rainfall, particulate P was the dominant form of P loss, dissolved P is often the dominant form of P loss under natural field conditions on the Prairies (Glozier et al., 2005; Sheppard et al., 2006; Little et al., 2007), probably because most natural runoff occurring during snowmelt over frozen soils and nearly level landscapes. Particulate P load in runoff and percolate showed significant correlations with the sediment loss indicating that runoff and percolate PP load increases with increasing sediment loss (Figure 7).

To investigate whether the concentration of P in sediments was influenced by the fertility treatments, sediment P concentration was calculated as the ratio of particulate P loss (mg) to sediment loss (g) from each tray. Sediment P concentration in runoff samples showed a significant fertility treatment x soil interaction (Table 7). In Lone Sand, where sediment loss was lower than in Newdale CL, the sediment P concentration was significantly higher in MAP treatment than in manure and check treatments (Table 7), while the liquid swine manure treatment had significantly higher runoff sediment P concentrations than the check treatment (Table 7). This effect was not seen in runoff samples from Newdale CL or with percolate samples from either soil.



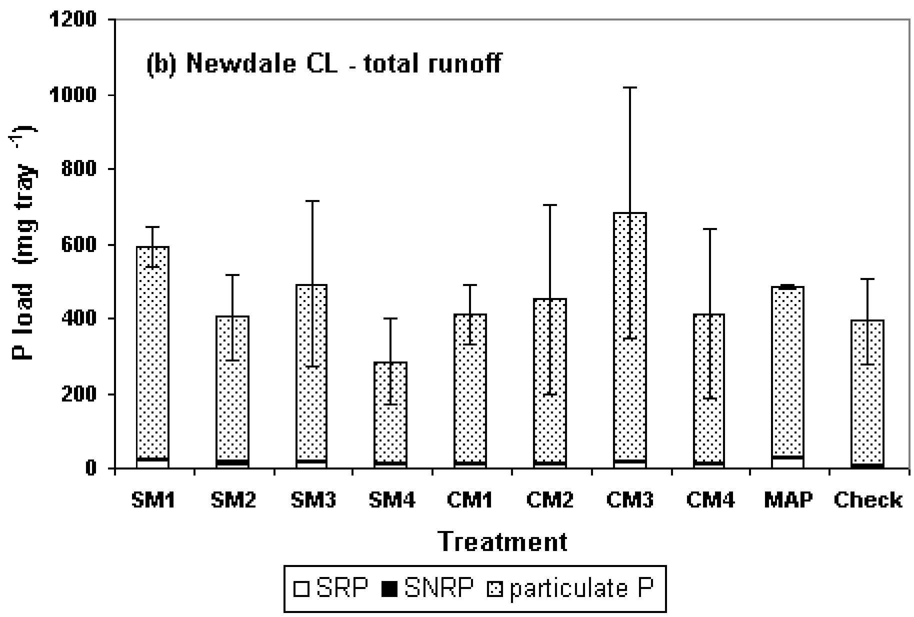
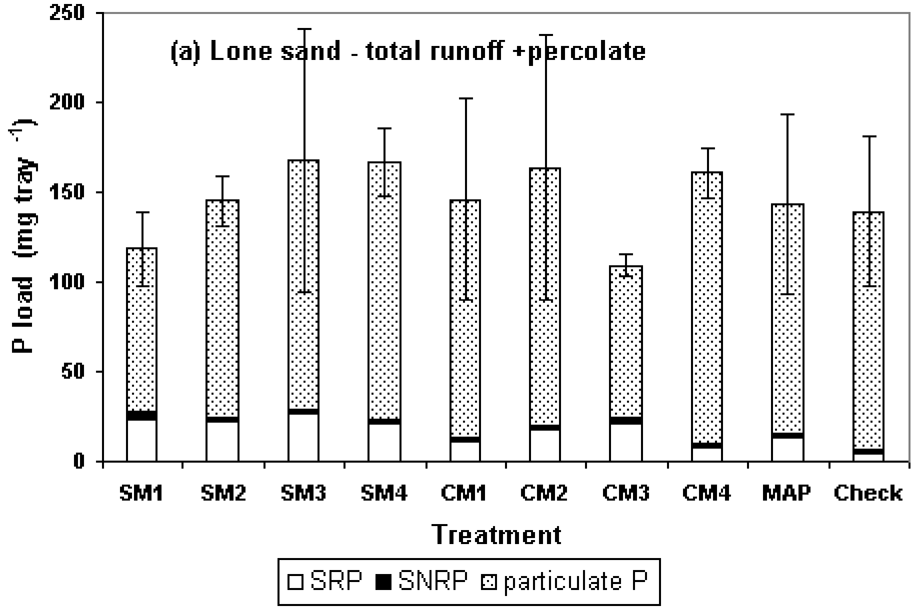


Figure 5. **Total runoff loads of SRP, SNRP and PP from different fertility treatments in (a) Lone Sand and (b) Newdale CL**



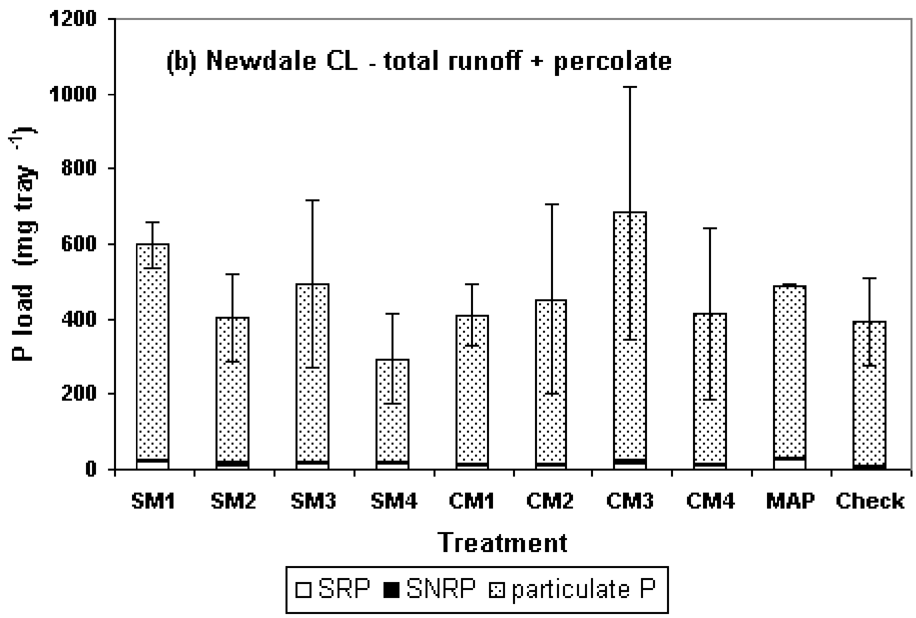


Figure 6. **Total percolate loads of SRP, SNRP and PP from different fertility treatments in (a) Lone Sand and (b) Newdale CL**

Table 7. Geometric means[1] of particulate P load, total P load and sediment P concentration in runoff (0-60 min) and percolate (0-60 min) in different fertility treatments

Effect	Particulate P load[2] (mg tray^{-1})		Total P load[2] (mg tray^{-1})		Sediment P conc'n[2] (mg g^{-1})	
	Runoff	Percolate	Runoff	Percolate	Runoff[3]	Percolate
Soil						
Lone Sand	121.7 b	1.75 a	132.9 b	6.71 a		1.75 a
Newdale CL	410.6 a	1.69 a	424.3 a	0.87 b		0.61 a
Fertility treatment						
Liquid swine manure	216.5 a	1.31 a	233.1 a	4.14 a		1.31 a
Solid cattle manure	227.5 a	0.97 a	242.3 a	2.58 a		0.97 a
MAP	230.6 a	1.29 a	249.6 a	2.94 a		1.29 a
Check	219.8 a	0.69 a	225.7 a	1.08 a		0.69 a
Soil x Fertility Trt.						
Lone Sand						
Liquid swine manure					2.55 b	
Solid cattle manure					2.18 bc	
MAP					5.81 a	
Check					1.23 c	
Newdale CL						
Liquid swine manure					1.19 a	
Solid cattle manure					1.01 a	
MAP					1.06 a	
Check					1.17 a	
ANOVA			**P>F**			
Soil	**<0.0001**	**0.1391**	**<0.0001**	**<0.0001**	**<0.0001**	**0.2677**
Fertility treatment	**0.9733**	**0.8532**	**0.9570**	**0.1434**	**0.0004**	**0.1418**
Soil x Fert. Trt	**0.8846**	**0.9015**	**0.9051**	**0.9081**	**0.0002**	**0.8070**

[1] Geometric means computed using Proc Mixed (SAS version 9.1) for two-way ANOVA considering different sources of manure as replicates; 2 soils, 4 fertility treatments (8 replicates for fertility treatments 1 and 2 and 2 replicates for fertility treatments 3 and 4).

[2] Means within the same column followed by the same lower case letter are not significantly different at $p \leq 0.05$ by Tukey-Kramer test

[3] Mean separation for main effects not shown since the interaction was significant ($p \leq 0.05$).

3.4.5. Relationship between SRP loss and inorganic P (P_i) fractions in manure

Water-P_i fraction in manure did not show a significant correlation with runoff SRP concentrations or loads in either soil (Table 8). In the Lone Sand, neither percolate SRP concentration nor load were correlated with the water-P_i fraction in manure. In the Newdale CL, percolate SRP concentration and load were significantly correlated with water-P_i fraction in manure; however, the percolate SRP load in the clay loam was negligible. The results of this study therefore suggest that the water-P_i fraction in manure does not predict the risk of SRP loss from manured soils after those manures have interacted with the soil.

Conversely, the $NaHCO_3$-P_i fraction in manure showed a significant correlation with runoff SRP concentration during the 0-30 min interval, and with the runoff SRP loads at 0-30 min, 30-60 min and 0-60 min, as well as with total runoff plus percolate loads at 0-60 min in the Newdale CL. In the Lone Sand, the $NaHCO_3$-P_i fraction in manure showed a significant correlation with the concentration and load of SRP in percolate but not for runoff (Table 8).

Labile inorganic P (water-P_i + $NaHCO_3$-P_i) was significantly correlated with runoff SRP concentration during the 0-30 min interval, and with the runoff SRP loads at 0-30 min, and 0-60 min, as well as total runoff plus percolate SRP load at 0-60 min in Newdale CL. In Lone Sand, the labile-P_i fraction in manure did not show a significant correlation with any form of SRP loss (Table 8).

In both soils, NaOH-P_i and HCl-P_i fractions in manure did not show a significant correlation with runoff or percolate SRP loss. Total Pi in manure showed significant correlations with runoff SRP concentration and runoff at 0-30 min and 30-60 min, as well as total runoff plus percolate SRP loads in Newdale CL, but not in Lone Sand (Table 8).

3.4.6. Relationship between SRP loss and total P (P_t) fractions in manure

Relationship between P loss and total P fractions in manure showed a similar trend as with inorganic P fractions. Water-P_t, NaOH- P_t and HCl-P_t fractions in manure did not show a significant correlation with runoff P loss in either soil. In the Newdale CL, $NaHCO_3$-P_t and labile-P_t in manure were correlated with runoff SRP concentration at 0-30 min, runoff SRP loads at 0-30, 30-60 and 0-60 min (Table 9, Figure 7). In Lone Sand, percolate SRP load was correlated with $NaHCO_3$ - P_t and labile- P_t; however, percolate SRP concentration was correlated with $NaHCO_3$ - P_t only. In both soils, the total SRP load (percolate + runoff) during the entire simulation period of 0-60 min was highly correlated with $NaHCO_3$-P_t and labile-P_t. Thus, when both soils were considered, $NaHCO_3$-P_t and labile- P_t fractions in manure predicted the total P loss better than other manure P forms. The homogeneity of regression test between SRP loss and labile-P_t indicated no significant difference in the slope of regression lines between the two soils, indicating that the same equation could be used to predict SRP loss using labile-P_t fraction (Figure 7).

3.4.7. Relationship between TP and PP loss and P fractions in manure

Runoff TP and PP loads did not show significant correlations with water-P_i and water-P_t fractions of manure in either soil. In Lone sand only, $NaHCO_3$-P_i, labile P_i (water-P_i + $NaHCO_3$-P_i) and total P_i fractions in manure showed significant negative correlations with runoff TP and PP loads (Table 10). This negative correlation on this sandy soil may be due to substantial infiltration and percolation of water and P from manures with high concentrations of labile P, leaving less P on the soil surface for these treatments. For example, in the Lone Sand soil, percolate TP load showed highly significant positive correlations with $NaHCO_3$ and labile P_i and P_t fractions. These types of correlations were not observed in the Newdale CL which had a higher clay content than Lone Sand and where infiltration and percolation of P and water were much less. Thus, in the Newdale CL, both $NaHCO_3$ and labile P_i showed significant positive relationships with runoff TP load. Total P (P_t) fractions in manure, in general, did not show significant relationships with runoff TP and PP loads in either soil (Table 10).

Table 8. Correlation coefficients (r) between inorganic P (P_i) in different manure P fractions and form of SRP loss (n=8)

Form of P loss	Soil	Correlation coefficient (r)					
		Water-P_i	$NaHCO_3$- P_i	Labile P_i[1]	NaOH- P_i	HCl-P_i	Total P_i
Runoff SRP conc. (0-30 min)	Lone Sand	0.36 NS	0.17 NS	0.31 NS	0.55 NS	0.01 NS	0.36 NS
	Newdale CL	0.37 NS	0.85 **	0.86 **	0.38 NS	-0.19 NS	0.78 *
Runoff SRP conc. (30-60 min)	Lone Sand	0.51 NS	0.30 NS	0.49 NS	0.49 NS	0.32 NS	0.48 NS
	Newdale CL	0.29 NS	0.45 NS	0.49 NS	0.49 NS	-0.21 NS	0.83 *
Percolate SRP conc. (0-60 min)	Lone Sand	-0.17 NS	0.71*	0.54 NS	0.57 NS	-0.29 NS	0.52 NS
	Newdale CL	0.82*	-0.09 NS	0.23 NS	-0.29 NS	0.15 NS	0.15 NS
Runoff SRP load (0-30 min)	Lone Sand	0.45 NS	0.18 NS	0.38 NS	0.45 NS	0.10 NS	0.52 NS
	Newdale CL	0.25 NS	0.97 ***	0.93***	0.40 NS	-0.12 NS	0.50 NS
Runoff SRP load (30-60 min)	Lone Sand	0.52 NS	0.45 NS	0.62 NS	0.48 NS	0.25 NS	0.68 NS
	Newdale CL	0.05 NS	0.85 **	0.55 NS	0.57 NS	-0.31 NS	0.68 NS
Runoff SRP load (0-60 min)	Lone Sand	0.49 NS	0.31 NS	0.49 NS	0.47 NS	0.29 NS	0.57 NS
	Newdale CL	0.18 NS	0.95 ***	0.88 **	0.48 NS	-0.25 NS	0.79 *
Percolate SRP load (0-60 min)	Lone Sand	-0.16 NS	0.76 *	0.58 NS	0.63 NS	-0.38 NS	0.54 NS
	Newdale CL	0.75 *	-0.06 NS	0.24 NS	-0.17 NS	0.13 NS	0.19 NS
Total Runoff plus Percolate SRP load (0-60 min)	Lone Sand	0.15 NS	0.68 NS	0.65 NS	0.68 NS	-0.11 NS	0.67 NS
	Newdale CL	0.30 NS	0.93 ***	0.92 **	0.45 NS	-0.23 NS	0.82 *

[1] Labile P_i = Water-P_i + $NaHCO_3$- P_i

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at $p \leq 0.05$

Table 9. Correlation coefficients (r) between total P (P_t) in different manure P fractions and form of SRP loss (n=8)

Form of P loss	Soil	Correlation coefficient (r)					
		Water-P_t	$NaHCO_3$- P_t	Labile P_t[1]	NaOH- P_t	HCl-P_t	Total P
Runoff SRP conc. (0-30 min)	Lone Sand	0.39 NS	0.47 NS	0.56 NS	0.10 NS	-0.10 NS	0.15 NS
	Newdale CL	0.48 NS	0.75 *	0.83 *	-0.07 NS	-0.26 NS	0.34 NS
Runoff SRP conc. (30-60 min)	Lone Sand	0.52 NS	0.54 NS	0.67 NS	0.09 NS	0.02 NS	0.33 NS
	Newdale CL	0.40 NS	0.49 NS	0.58 NS	0.01 NS	-0.27 NS	0.07 NS
Percolate SRP Conc. (0-60 min)	Lone Sand	-0.12 NS	0.89 **	0.70 NS	0.12 NS	-0.41 NS	0.27 NS
	Newdale CL	0.84**	-0.12 NS	0.24 NS	-0.40 NS	0.21 NS	0.06 NS
Runoff SRP load (0-30 min)	Lone Sand	0.42 NS	0.46 NS	0.56 NS	0.13 NS	0.22 NS	0.40 NS
	Newdale CL	0.30 NS	0.91 **	0.90 **	0.09 NS	-0.21 NS	0.59 NS
Runoff SRP load (30-60 min)	Lone Sand	0.51 NS	0.64 NS	0.75 *	0.14 NS	0.18 NS	0.55 NS
	Newdale CL	0.11 NS	0.94 ***	0.85 **	0.19 NS	-0.38 NS	0.45 NS
Runoff SRP load (0-60 min)	Lone Sand	0.47 NS	0.55 NS	0.66 NS	0.13 NS	0.20 NS	0.47 NS
	Newdale CL	0.23 NS	0.94 ***	0.90 **	0.14 NS	-0.29 NS	0.55 NS
Percolate SRP load (0-60 min)	Lone Sand	-0.09 NS	0.92 **	0.75 *	0.13 NS	-0.51 NS	0.23 NS
	Newdale CL	0.80 *	-0.08 NS	0.26 NS	-0.37 NS	0.14 NS	-0.01 NS
Total Runoff plus Percolate SRP load (0-60 min)	Lone Sand	0.19 NS	0.92 **	0.86 **	0.16 NS	-0.25 NS	0.41 NS
	Newdale CL	0.37 NS	0.93 ***	0.94 ***	0.07 NS	-0.26 NS	0.54 NS

[1] Labile P_t = Water-P_t + $NaHCO_3$- P_t

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at $p \leq 0.05$

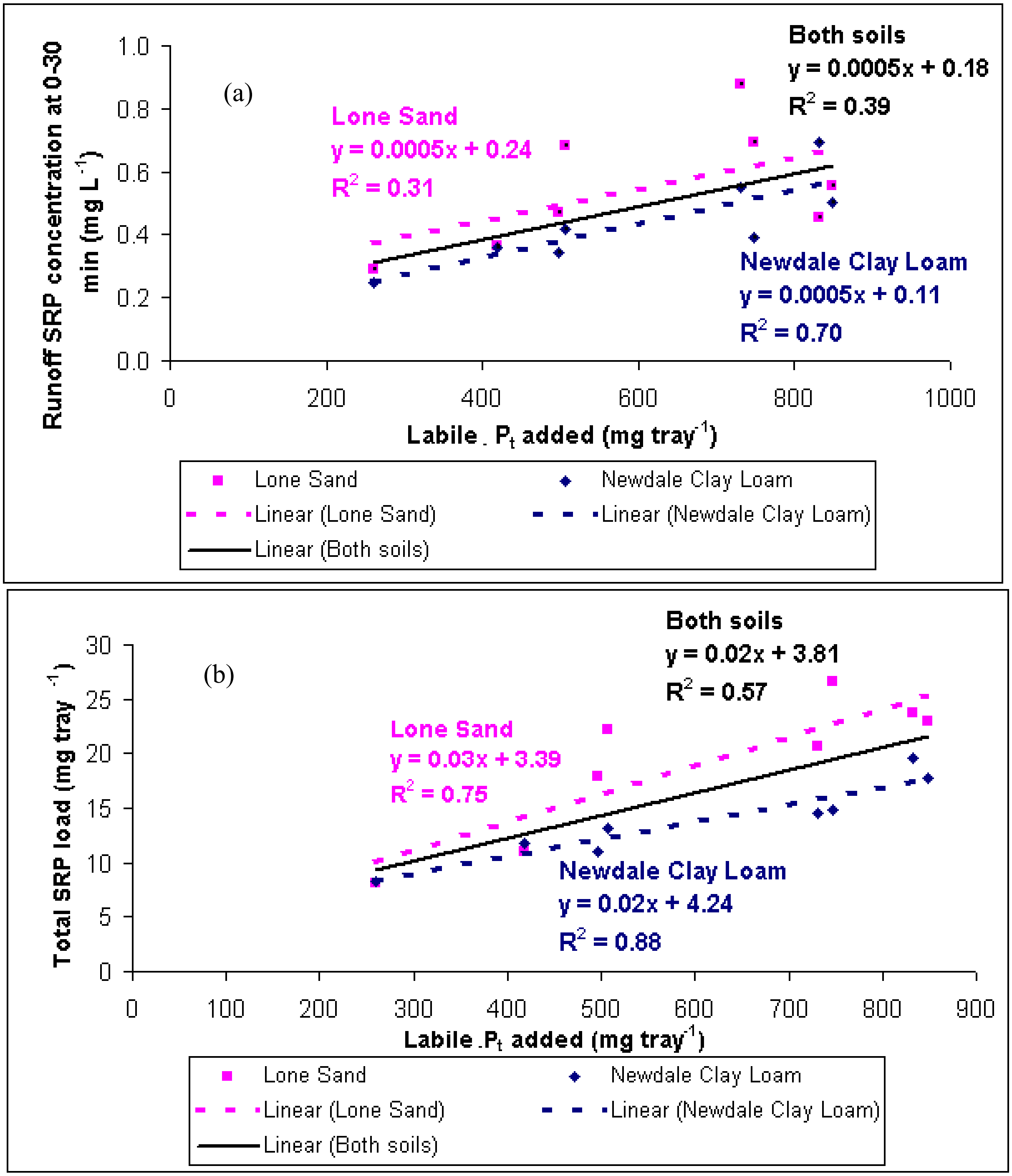


Figure 7. **Relationship between labile–P_t fraction in manure added and P loss (a) SRP concentration in 0-30 min runoff (b) total runoff plus percolate SRP load (Labile P_t = Water-P_t + $NaHCO_3$- P_t)**

Table 10. Correlation coefficients (r) between total (P_t) and inorganic P (P_i) in different manure P fractions and TP and PP loss (n=8)

Form of P loss	Soil	Correlation coefficient (r)			
		Water-P_i	**$NaHCO_3$- P_i**	**Labile P_i[1]**	**Total P_i**
Runoff TP load	**Lone Sand**	-0.07^{NS}	-0.91**	-0.81*	-0.73*
(0-60 min)	**Newdale CL**	0.20^{NS}	0.93***	0.88**	0.78*
Runoff PP load	**Lone Sand**	-0.14^{NS}	-0.95***	-0.87**	-0.80*
(0-60 min)	**Newdale CL**	0.001^{NS}	0.73*	0.63^{NS}	0.54^{NS}
Percolate TP load	**Lone Sand**	0.29^{NS}	0.79*	0.79*	0.67^{NS}
(0-60 min)	**Newdale CL**	0.66^{NS}	0.24^{NS}	0.45^{NS}	0.36^{NS}
Percolate PP load	**Lone Sand**	0.80*	0.19^{NS}	0.46^{NS}	0.32^{NS}
(0-60 min)	**Newdale CL**	0.61^{NS}	0.31^{NS}	0.49^{NS}	0.40^{NS}
Runoff + percolate	**Lone Sand**	-0.01^{NS}	-0.84**	-0.73*	-0.67^{NS}
TP load (30-60 min)	**Newdale CL**	0.02^{NS}	0.76*	0.64^{NS}	0.56^{NS}
		Water-P_t	**$NaHCO_3$- P_t**	**Labile P_t[2]**	**Total P_t**
Runoff TP load	**Lone Sand**	-0.09^{NS}	-0.69^{NS}	-0.62^{NS}	-0.67^{NS}
(0-60 min)	**Newdale CL**	-0.02^{NS}	0.64^{NS}	0.53^{NS}	0.64^{NS}
Runoff PP load	**Lone Sand**	-0.15^{NS}	-0.75*	-0.70^{NS}	-0.73*
(0-60 min)	**Newdale CL**	-0.03^{NS}	0.62^{NS}	0.52^{NS}	0.64^{NS}
Percolate TP load	**Lone Sand**	0.38^{NS}	0.93***	0.95***	0.35^{NS}
(0-60 min)	**Newdale CL**	0.76*	0.16^{NS}	0.45^{NS}	-0.03^{NS}
Percolate PP load	**Lone Sand**	0.78*	0.13^{NS}	0.43^{NS}	0.40^{NS}
(0-60 min)	**Newdale CL**	0.72*	0.22^{NS}	0.48^{NS}	-0.04^{NS}
Runoff + percolate	**Lone Sand**	-0.02^{NS}	-0.56^{NS}	-0.49^{NS}	-0.67^{NS}
TP load (30-60 min)	**Newdale CL**	0.002^{NS}	0.65^{NS}	0.55^{NS}	0.64^{NS}

[1] Labile P_i = Water-P_i + $NaHCO_3$- P_i
[2] Labile P_t = Water-P_t + $NaHCO_3$- P_t
***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; ^{NS} indicates not significant at $p \leq 0.05$

3.4.8. Soil test P after incubation prior to runoff

The initial concentration of Olsen P in Newdale CL was higher than in Lone Sand (Table 1). After incubation, a similar trend was observed in the check treatments, with all four soil test P methods (Appendix 9 and Table 11). In manure or fertilizer treated soils after incubation, phosphorus extracted after incubation with Mehlich 3, modified Kelowna and Olsen was often higher in Newdale CL than in Lone Sand, while P extracted with water was greater in Lone Sand compared to Newdale CL. This is very likely due to the higher P retention capacity in Newdale CL which may have converted a relatively higher proportion of manure P into less available forms during incubation than in the Lone Sand soil.

Main and interactive effects of soil and fertility treatments were significant for P extracted by all four STP methods (Table 11). In Lone Sand, P extracted by all soil test P methods was significantly higher in liquid swine manure and MAP treated soils than in solid cattle manure treated and unamended soils. In Newdale CL, however, P extracted with Mehlich 3, modified Kelowna and Olsen was significantly higher in MAP treated soils than in liquid swine manure treated soils, both of which were higher than in solid cattle manure treated and unamended soils (Table 11). Water extractable P in Newdale CL did not show significant differences among treatments. In both soils and with all methods, the MAP treatment resulted in the highest concentration of extractable P, while the check and solid cattle manure treatments resulted in the lowest values, which were not significantly different from each other.

3.4.9. Relationship between P loss and STP

Simple linear regression analysis conducted separately for the two soils showed that the concentration of SRP in runoff at 0-30 and 30-60 min showed highly significant relationships with Mehlich 3-P, modified Kelowna-P and Olsen-P in both soils (Table 12, Appendix 10 and 11). In Lone Sand, 53-55% of the variation in runoff SRP concentration at 0-30 min was explained by a linear relationship with P extracted by these three STP methods, whereas for Newdale CL, the linear relationship explained 48 – 54 % of the variation (Figure 8). Water extractable P on the other hand, was poorly related to the SRP concentration in runoff, even though the relationship was often significant at $p \leq 0.05$. As a result, only 16-32% of the total variation in runoff SRP concentration was explained by the variation in water soluble P when regression analysis was conducted for the two soils separately (Figure 8d). Similar trends were observed when regression analyses were conducted pooling both soils (Table 12 and Appendix 12).

In Lone Sand, most of the SRP losses during runoff occurred during the first 30 min and only small amounts were lost during the 30-60 min period. The relationships between runoff load and STP methods indicated highly significant correlations for Mehlich 3-P, modified Kelowna- P and Olsen P and runoff SRP load at 0-30 min and weaker, yet generally significant relationships with runoff SRP load at 30-60 min (Table 12).

For Lone Sand, SRP runoff load for the entire simulation period showed a highly significant relationship with Mehlich 3, modified Kelowna and Olsen extractable P, but only 35 – 39% of the variation was explained by the variation in extractable P measured by these three methods. In Newdale CL, runoff SRP load at 0-30 min, 30-60 min and the total runoff SRP loss for the entire 60 min period showed a highly significant relationship with Mehlich 3, Modified Kelowna and Olsen extractable P. Differences in extractable P by these three STP methods explained 54–60 % of the variation in total SRP runoff loss from the Newdale CL (Figure 9).

Water extractable P, in contrast, showed a highly significant relationship with runoff SRP load only in Newdale CL at 0-30 min. The relationships between water extractable P and runoff SRP loads were weak, but significant at 0-30 min in Lone Sand and at 30-60 min in Newdale CL, while 30-60 min runoff SRP load did not show a significant relationship with water extractable P in Newdale CL. Total runoff SRP load in Lone Sand was not significantly correlated with water extractable P, whereas in Newdale CL the total SRP load was significantly correlated with water extractable P, explaining 64% of the variation. When both soils were considered, Mehlich 3, modified Kelowna and Olsen extractable P were better than water extractable P for predicting the SRP load with runoff, while Olsen P was superior to Mehlich 3 and modified Kelowna, explaining 70% of the variation in runoff SRP load.

In Newdale CL, SRP loss with percolate was negligible and poorly correlated with all soil test P methods, whereas an appreciable quantity of SRP was lost with percolate in Lone Sand (Figure 10 and Table 12). The percolate SRP concentration in Lone Sand showed a stronger relationship with water extractable P than with P extracted by more aggressive extractants such as Mehlich 3, modified Kelowna and Olsen. Even though water extractable P was poor for predicting SRP loss with runoff, it was better for predicting SRP loss with percolate. This may be because the degree of interaction between runoff water and soil is less than for percolate water and soil, and therefore more closely resembles the mixing conditions for the laboratory method of P extraction with water. Conversely, loss of SRP with runoff water was more related to the P extracted by stronger extractants that remove labile P forms in addition to the water extractable forms. This result may be due to preferential, continuous depletion of P from the surface soil during runoff, drawing P from the surface soil's labile reserves that are not normally measured as "water soluble" during laboratory extraction. Runoff over fine-textured soils in particular, where the effective depth of interaction with runoff water is very shallow, may act as a sink for P that resembles the effect of root uptake of P from soil solution. Therefore, agronomic P test methods such as the Olsen test are able to measure not only the intensity of water soluble P available to runoff during the initial stages of the event, but also the quantity of labile reserve P that replenishes the water soluble pool as the runoff event progresses.

The regression equations between runoff SRP concentration at 0-30 min and soil test P with Mehlich 3, modified Kelowna and Olsen showed a slightly higher intercept and greater slope with Lone Sand than with Newdale CL (Figure 8). This implies that at any level of soil test P, the runoff SRP concentration initially is greater in Lone Sand than in Newdale CL. This again points to the low buffering ability in Lone Sand, releasing P rapidly, whereas Newdale CL, with a higher P buffering ability releases P slowly. This trend, however, was not observed with the SRP load (Figure 9). The regression equations between SRP load and soil test P with all methods showed a greater slope in Newdale CL than in Lone Sand. Therefore, at any level of soil test P, the total runoff SRP load for the entire 60 min simulation period was greater in the Newdale CL than in Lone Sand.

Relationships between TDP loads with STP were similar to those between SRP loads and STP (Table 12). Mehlich 3-P, modified Kelowna-P and Olsen P were highly correlated to TDP loads while water extractable P was poorly correlated with TDP loads. Total P and particulate P did not show significant correlations with P extracted by any STP method.

Table 11. Least square means[1] of soil P extracted (mg kg^{-1}) by different STP methods after incubation and prior to the runoff experiment

Effect[2]	P extracted by different STP methods[3] (mg kg^{-1})			
	Mehlich 3	Modified Kelowna	Olsen	Water
Soil x Fertility Trt.				
Lone Sand				
Liquid swine manure	68.6 a	52.8 a	43.8 a	17.1 a
Solid cattle manure	42.8 b	31.9 b	26.7 b	8.4 b
MAP	73.4 a	54.8 a	45.3 a	20.1 a
Check	33.7 b	20.2 b	19.6 b	4.2 b
Newdale CL				
Liquid swine manure	63.8 b	46.8 b	42.9 b	8.6 a
Solid cattle manure	50.3 c	36.3 c	33.9 c	7.1 a
MAP	89.5 a	65.9 a	63.3 a	11.9 a
Check	42.3 c	29.7 c	29.5 c	4.9 a
ANOVA	**P>F**			
Soil	**0.0161**	**0.0640**	**<0.0001**	**0.0013**
Fertility treatment	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Soil x Fert. Trt	**0.0208**	**0.0259**	**0.0039**	**0.0054**

[1] Least square means computed using Proc Mixed (SAS version 9.1) for two-way ANOVA considering different sources of manure as replicates; 2 soils, 4 fertility treatments (8 replicates for fertility treatments 1 and 2 and 2 replicates for fertility treatments 3 and 4).
[2] Mean separation for main effects not shown since the interaction was significant ($p \leq 0.05$).
[3] Means within the same column followed by the same lower case letter are not significantly different at $p \leq 0.05$ by Tukey-Kramer test.

Table 12. Correlation coefficients (r) between soil test P and P loss

Soil	Replicate	Correlation coefficient (r)			
		Mehlich 3	Modified Kelowna	Olsen	Water
Lone Sand (n=20)					
SRP conc.	Runoff 0-30 min	0.74 ***	0.72 ***	0.74 ***	0.54 *
	Runoff 30-60 min	0.63 **	0.61 **	0.64 **	0.39 NS
	Percolate 0-60 min	0.59 **	0.68 ***	0.65 **	0.69 ***
SRP load	Runoff 0-30 min	0.61 **	0.64 **	0.64 **	0.47 *
	Runoff 30-60 min	0.50 *	0.52 *	0.52 *	0.34 NS
	Percolate 0-60 min	0.59 **	0.66 **	0.64 **	0.66 **
	Total SRP runoff	0.59 **	0.62 **	0.62 **	0.44 NS
	Runoff + percolate SRP loss	0.70 ***	0.76 ***	0.75 ***	0.66 **
	% loss	0.67 **	0.73 ***	0.72 ***	0.63 **
TDP load	Total SRP runoff	0.57*	0.61**	0.61**	0.44NS
	Runoff + percolate SRP loss	0.72***	0.77***	0.77***	0.64***
Newdale CL (n=20)					
SRP conc.	Runoff 0-30 min	0.70 ***	0.71 ***	0.73 ***	0.56 *
	Runoff 30-60 min	0.69 ***	0.70 ***	0.74 ***	0.45 *
	Percolate 0-60 min	0.42 NS	0.41 ns	0.50 *	0.32 NS
SRP load	Runoff 0-30 min	0.70 ***	0.74 ***	0.70 ***	0.65 ***
	Runoff 30-60 min	0.71 ***	0.74 ***	0.72 ***	0.58 **
	Percolate 0-60 min	-0.17 NS	-0.17 NS	-0.09 NS	-0.23 NS
	Total SRP runoff	0.74 ***	0.77 ***	0.74 ***	0.64 **
	Runoff + percolate SRP loss	0.72 ***	0.76 ***	0.73 ***	0.62 **
	% loss	0.79 ***	0.81 ***	0.83 ***	0.59 **
TDP load	Total SRP runoff	0.72***	0.76***	0.72***	0.63**
	Runoff + percolate SRP loss	0.70***	0.74***	0.71***	0.61**
Both soils (n=40)					
SRP conc.	Runoff 0-30 min	0.68 ***	0.70 ***	0.66 ***	0.53 ***
	Runoff 30-60 min	0.63 ***	0.59 ***	0.71 ***	0.07 NS
SRP load					
	Percolate 0-60 min	0.29 NS	0.40 *	0.24 ns	0.72 ***
SRP load	Runoff 0-30 min	0.65 ***	0.68 ***	0.65 ***	0.41 **
	Runoff 30-60 min	0.57 ***	0.55 ***	0.64 ***	0.04 NS
	Percolate 0-60 min	0.22 NS	0.32 *	0.14 ns	0.69 ***
	Total SRP runoff	0.66 ***	0.66 ***	0.70 ***	0.23 NS
	Runoff + percolate SRP loss	0.66 ***	0.72 ***	0.64 ***	0.65 ***
	% loss	0.67 ***	0.72 ***	0.66 ***	0.63 ***
TDP load	Total SRP runoff	0.65***	0.66***	0.69***	0.25NS
	Runoff + percolate SRP loss	0.65***	0.72***	0.63***	0.67***

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at $p \leq 0.05$

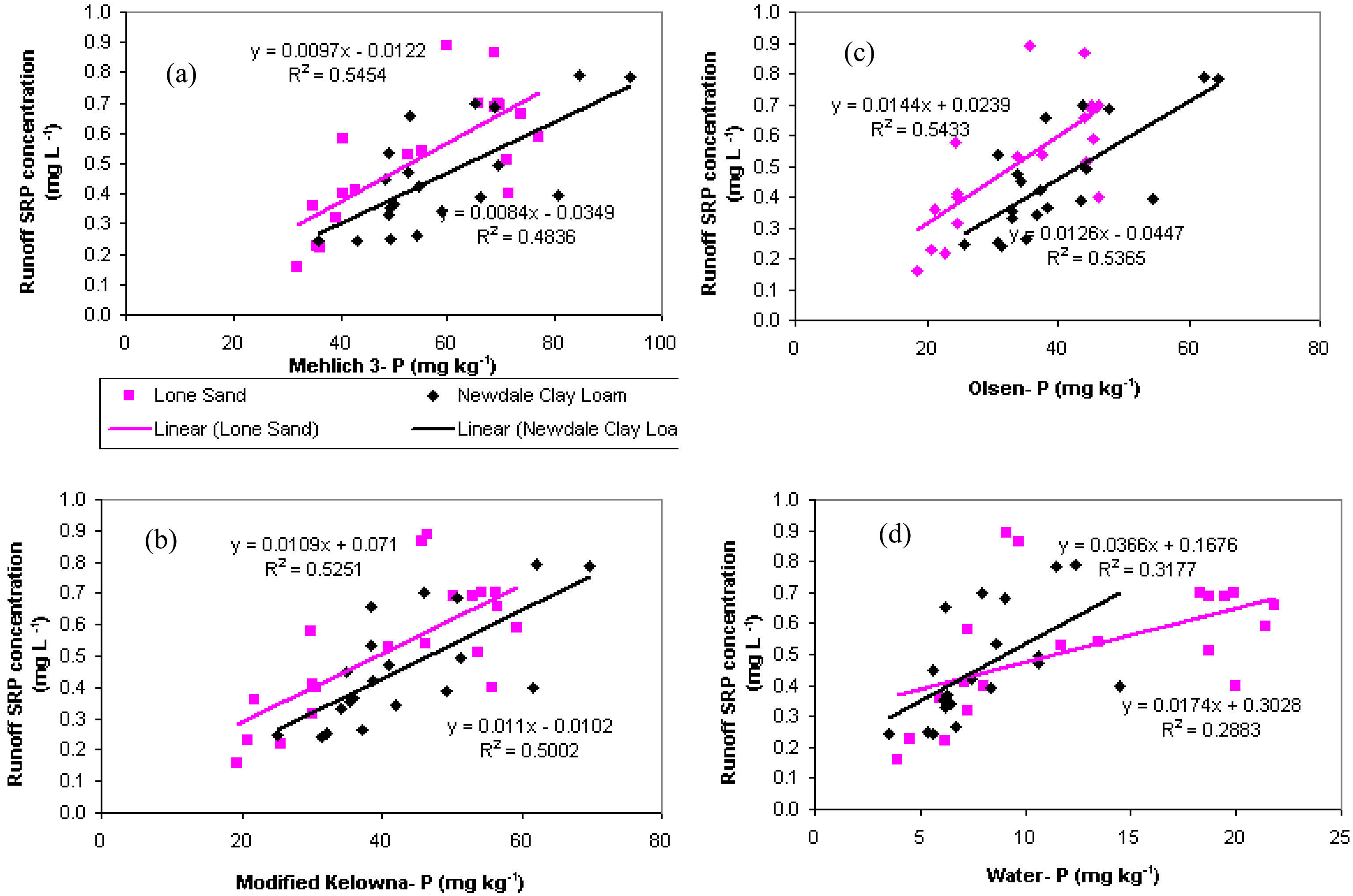


Figure 8. **Relationship between P extracted by different STP methods and runoff SRP concentration at 0-30 min (a) Mehlich 3-P (b) Modified Kelowna -P (c) Olsen P and (d) Water extractable P**

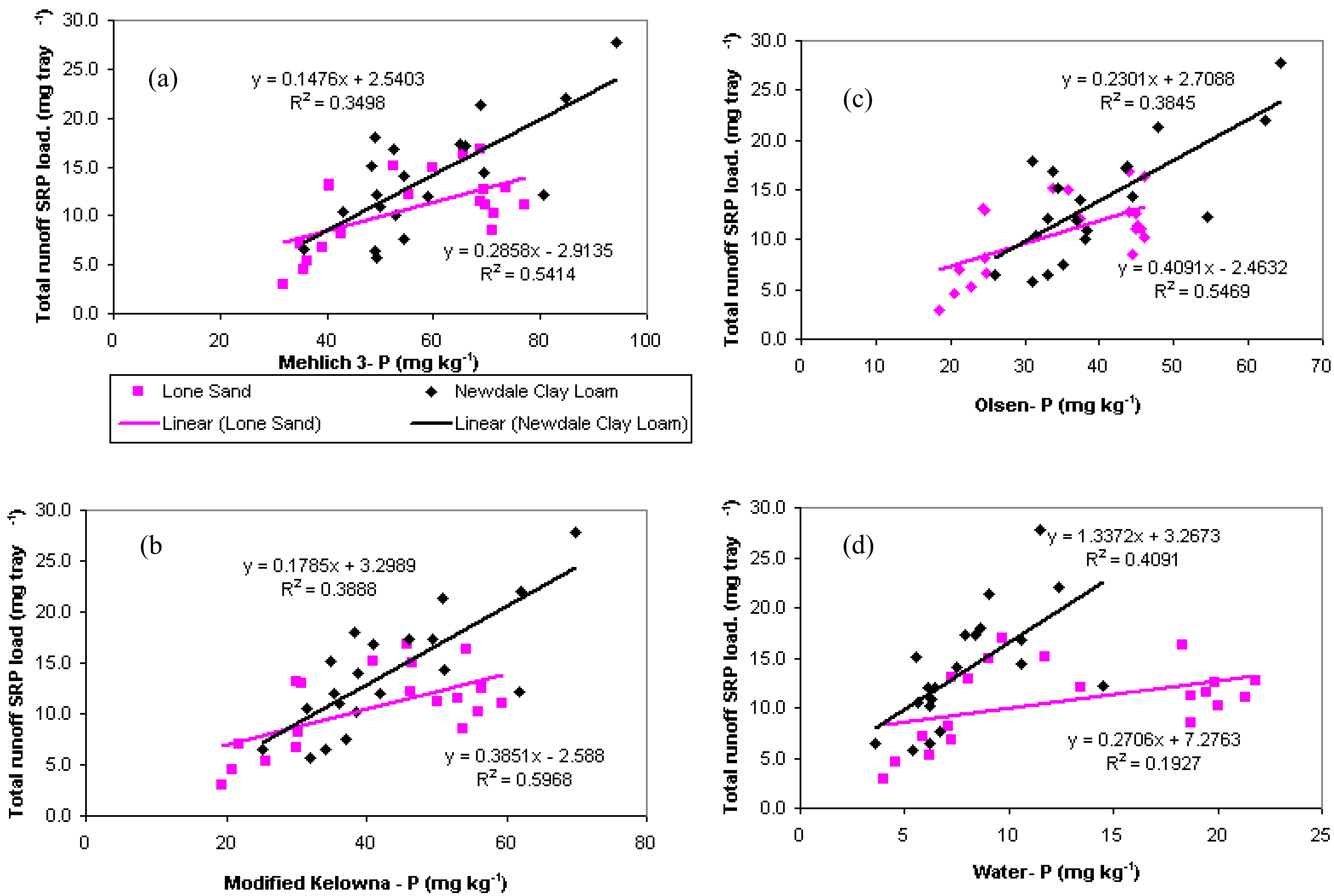


Figure 9. **Relationship between P extracted by different STP methods and runoff SRP load (a) Mehlich 3-P (b) Modified Kelowna -P (c) Olsen-P and (d) Water extractable P**

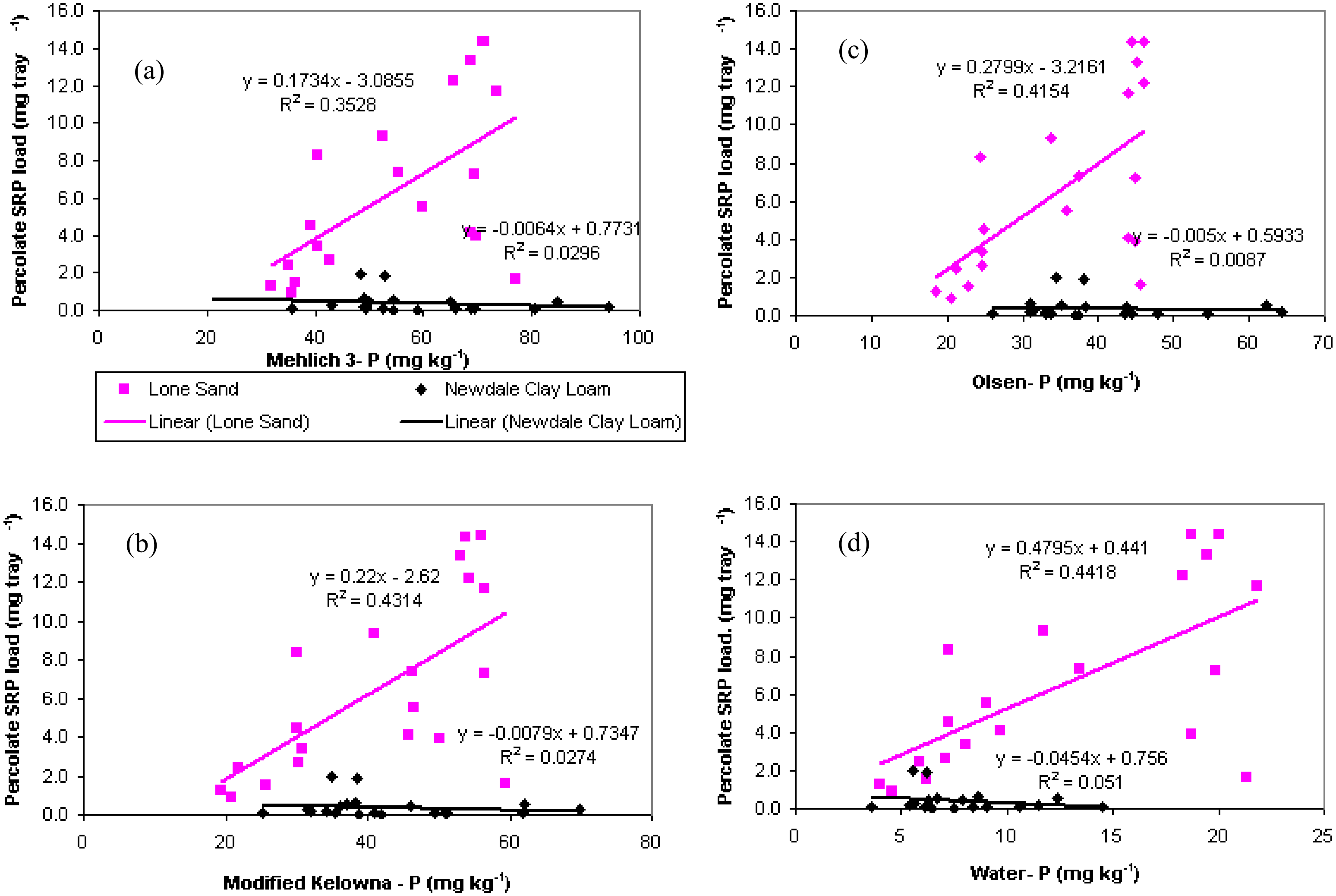


Figure 10. **Relationship between P extracted by different STP methods and percolate SRP load (a) Mehlich 3-P (b) Modified Kelowna –P (c) Olsen P and (d) Water extractable P**

3.5. Leaching study

3.5.1. Breakthrough curves for SRP and TDP

Breakthrough curves for SRP in Lone Sand showed higher peaks in liquid swine manure and MAP treatments than in solid cattle manure and check treatments (Figure 11). The differences between the two replicates were small (Appendix 13). The peak SRP concentrations in liquid swine manure treatments ranged between 14.6 mg L^{-1} in SM1 treatment to 27.8 mg L^{-1} in SM4 treatment with an average of 22.6 mg L^{-1}. The MAP treatment had a peak SRP concentration of 20.5 mg L^{-1}, which was lower than in liquid swine manure treatments with the exception of SM1 treatment. The peak SRP concentrations in solid cattle manure treatments ranged from 4.3 to 12.3 mg L^{-1} with an average of 7.8 mg L^{-1}. The average peak SRP concentration with solid cattle manure treatments was significantly ($p \leq 0.05$) lower than with liquid swine manure treatments. The check treatment had the lowest peak SRP concentration of 3.6 mg L^{-1}. In liquid swine manure and MAP treatments, the peak concentration was observed when about 1.0 pore volume has been eluted. In solid cattle manure and check treatments the peak was observed when about 1.5 pore volumes were eluted. The shape of the peak also was different among fertility treatments, with a broader base in solid cattle manure treatments when compared to liquid swine manure and MAP treatments. This implies that in liquid swine manure and MAP treatments, the release of SRP is more rapid than with solid cattle manure treatments, very likely due to the higher amounts of P in more soluble forms in liquid swine manure and MAP compared to solid cattle manure (Figure 1).

The breakthrough curves in Newdale CL showed lower peak concentrations in all the fertility treatments (Figure 12) compared to the corresponding treatments in Lone Sand

(Figure 11). Thus, even though the same amount of P was applied with manure and MAP treatments of both soils, less P was eluted in the Newdale CL, because of its higher ability of this soil to retain P. The peak SRP concentrations in liquid swine manure treatments ranged from 4.0 to 5.6 mg L^{-1}, with an average of 4.8 mg L^{-1}, whereas peak SRP concentrations in solid cattle manure treatments ranged from 3.6 to 4.7 mg L^{-1} with an average of 4.1 mg L^{-1}. The MAP treatment gave the highest peak SRP concentration of 7.9 mg L^{-1}, while the peak SRP concentration in the check treatment was 2.9 mg L^{-1}. The concentrations of TDP in volume-weighted combined samples were slightly higher than SRP concentrations (Appendix 15 and 16). More than 95% of TDP were in SRP forms and soluble non-reactive P (SNRP) forms contributed to less than 6% of TDP.

3.5.2. Total SRP loss in different fertility treatments during elution of 3.5 pore volumes

Two-factor ANOVA revealed highly significant main and interaction effects between soil and manure type on total SRP loss during the elution of 3.5 pore volumes of water (Table 13). Total SRP loss during the elution of 3.5 pore volumes of water in Lone Sand was significantly greater than in Newdale CL for the corresponding manure and MAP treatments, even though, in the check treatment the SRP loss was similar in the two soils. This implies that more of the added P in the form of manure or fertilizer was retained in the Newdale CL. In Lone Sand, SRP loss was significantly higher in liquid swine manure and MAP treated columns than in solid cattle manure treated columns, while the SRP loss from solid cattle manure treated columns were significantly higher than from unamended columns (Table 13). There was no significant difference between SRP loss from liquid swine manure and MAP treated columns (Table 13 and Figure 13).

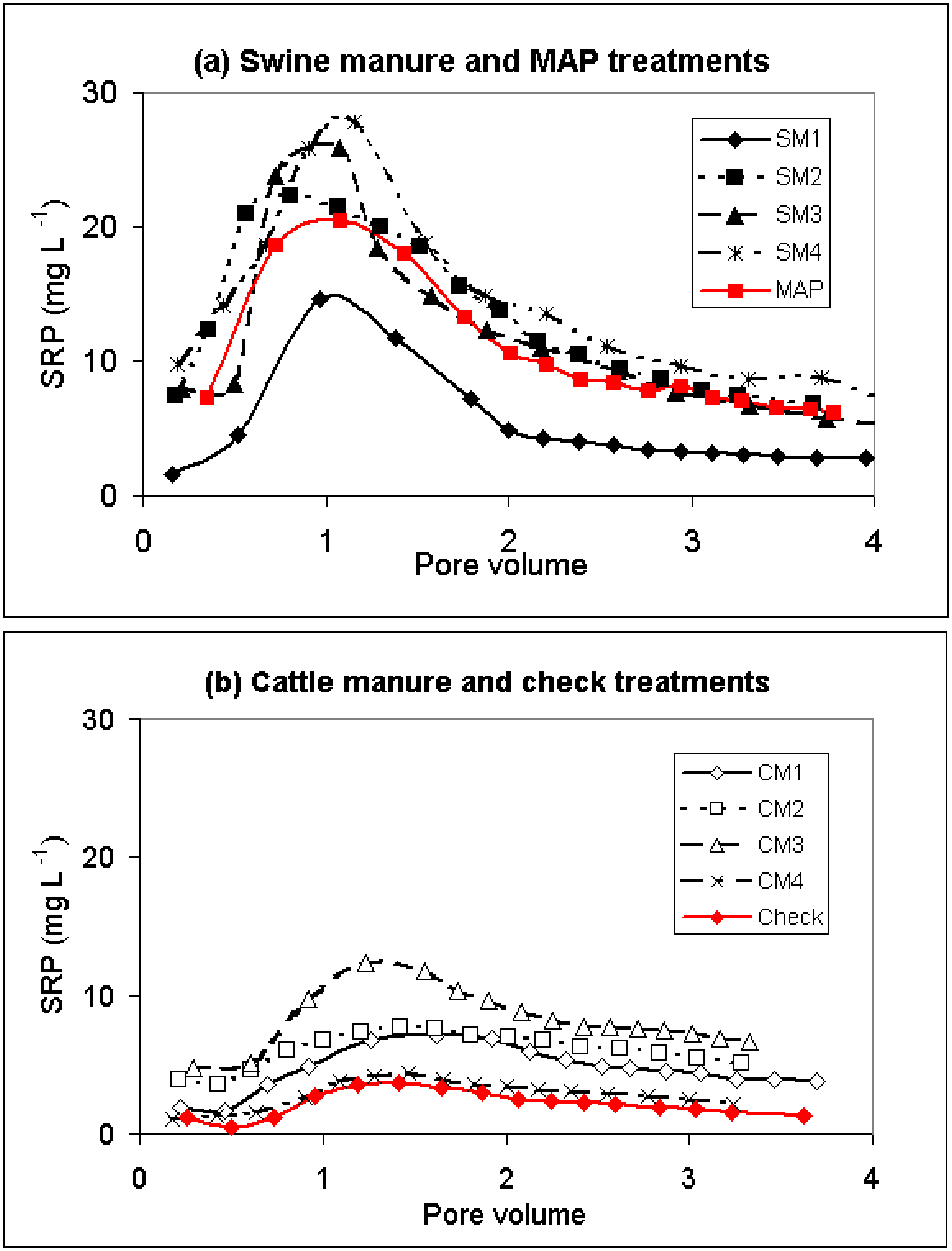


Figure 11. Breakthrough curves in Lone Sand (a) liquid swine manure and MAP treatments (b) solid cattle manure and check treatments

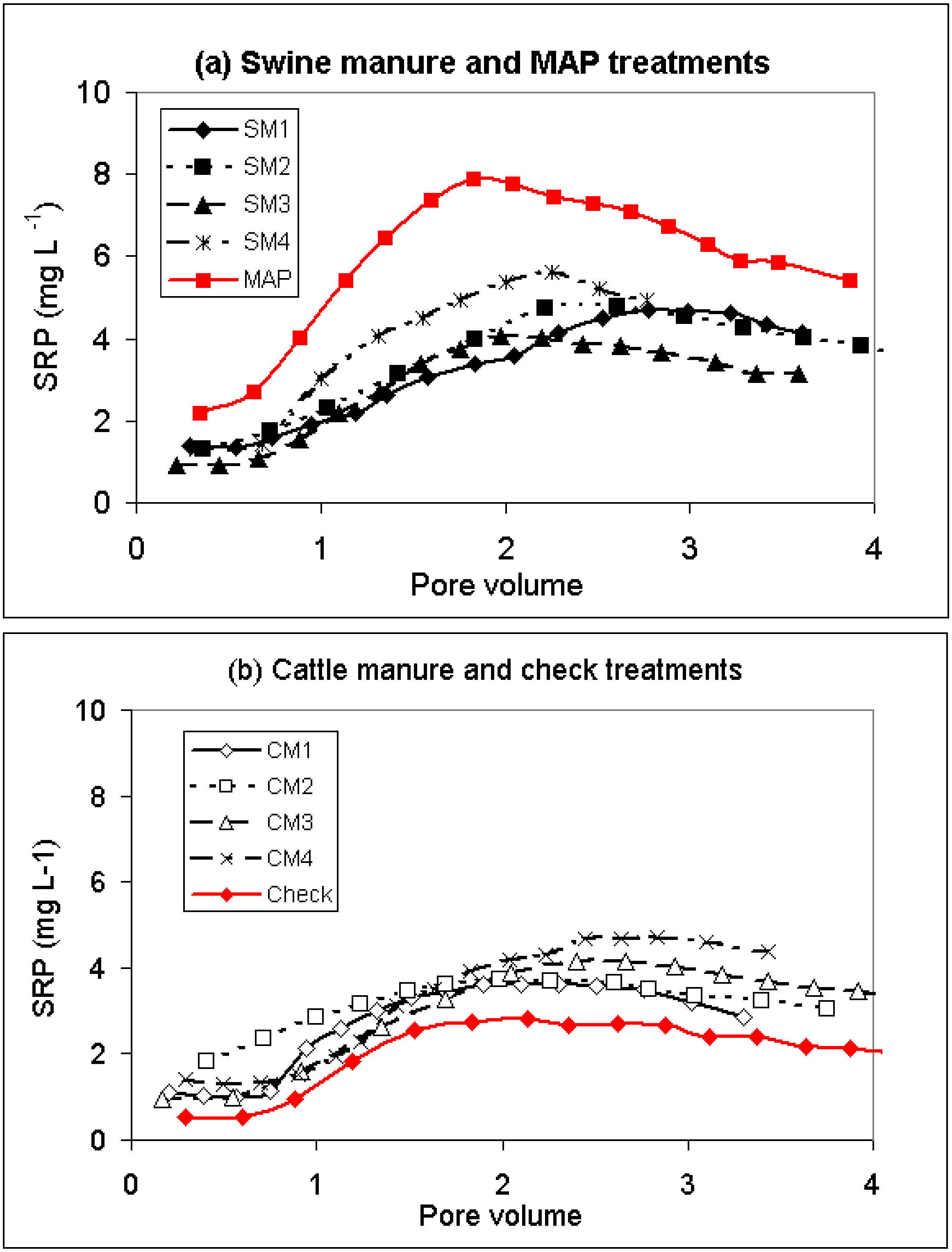


Figure 12. **Breakthrough curves in Newdale CL (a) liquid swine manure and MAP treatments (b) solid cattle manure and check treatments**

Table 13. Geometric means[1] of total SRP loss during 3.5 pore volume of elution in different treatments

Effect[2]	SRP loss during elution of 3.5 pore volume[3] (mg column^{-1})
Soil x Fertility Treatment	
Lone Sand	
Liquid swine manure	25.2 a
Solid cattle manure	10.7 b
MAP	26.4 a
Check	4.6 c
Newdale CL	
Liquid swine manure	7.7 ab
Solid cattle manure	7.1 ab
MAP	13.5 a
Check	4.9 b
ANOVA	**P > F**
Soil	**<0.0001**
Fertility treatment	**<0.0001**
Soil x Fertility Treatment	**0.0005**

[1] Geometric means computed using Proc Mixed (SAS version 9.1) for two-way ANOVA considering different sources of manure as replicates; 2 soils, 4 fertility treatments (8 replicates for fertility treatments 1 and 2 and 2 replicates for fertility treatments 3 and 4).
[2] Mean separation for main effects not shown since the interaction was significant ($p \le 0.05$).
[3] Means within the same column followed by the same lower case letter are not significantly different at $p \le 0.05$ by Tukey-Kramer test.

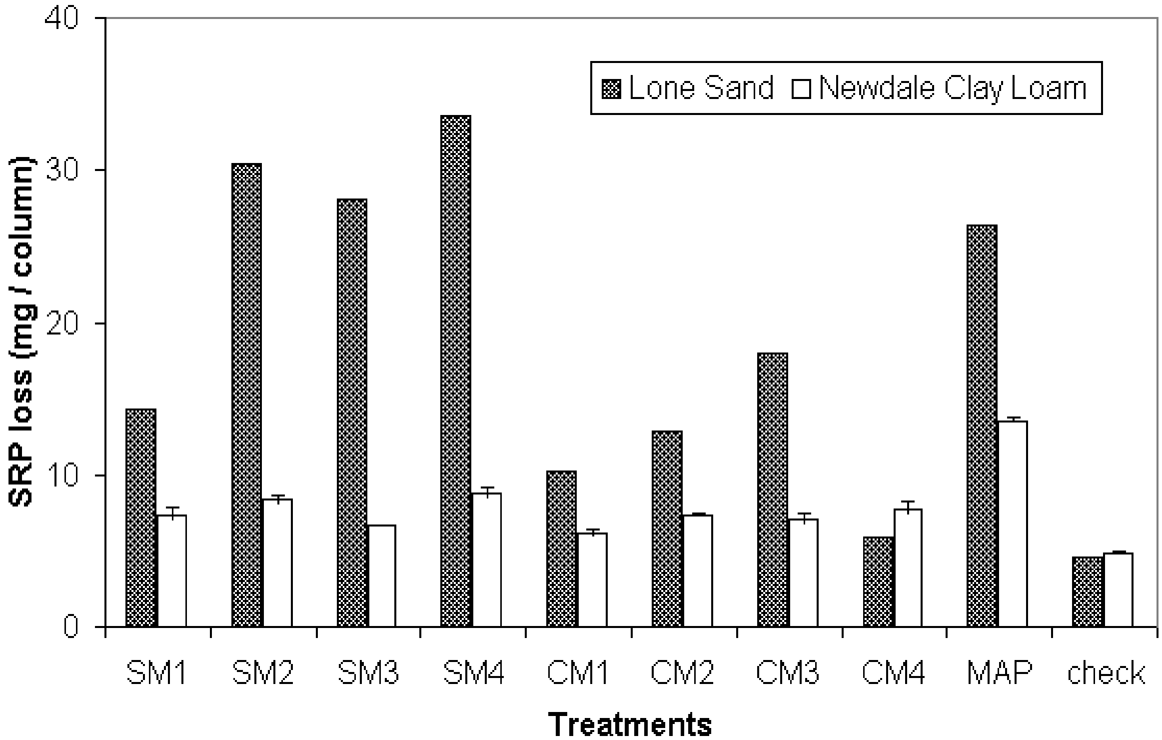


Figure 13. Total SRP loss with the elution of 3.5 pore volumes of water in different fertility treatments in Lone Sand and Newdale CL

In Newdale CL, total SRP loss during 3.5 pore volume of water eluted in MAP treated columns was significantly higher than from unamended columns (Table 13). The differences between solid cattle manure, liquid swine manure and MAP treatments were not significant for total SRP loss. This is likely due to the high retention of P in this soil. The differences in results between the percolate loss in runoff simulation study and leaching loss in column study could be the low rainfall intensity of 12.5 mm h^{-1} in column leaching study compared to 75 mm h^{-1} in the runoff study.

3.5.3. Relationships between SRP loss and P fractions in manure

In Lone Sand, only the NaOH-P_i fraction in manure showed a significant correlation with total SRP loss during the elution of 3.5 pore volumes of water (Table 14). In Newdale CL, none of the manure P forms showed a significant correlation with SRP loss, perhaps due to the greater ability of Newdale CL to retain P, which was apparent with the low amount of SRP loss, irrespective of the fertility treatment (Figure 13).

3.5.4. Soil test P after incubation

Similar to the soil test values measured prior to the runoff study, the main effect of fertility treatment and the interaction effect of fertility x soil were significant for P extracted by Mehlich 3, modified Kelowna and water extraction. In Lone Sand, liquid swine manure- and MAP- treated soils had significantly higher soil test P than solid cattle manure treated and unamended soils, using these three extraction methods . In Newdale CL, differences in these STP values for the various fertility treatments after incubation were not significant (Table 15). The high buffering ability in the Newdale CL soil may have converted added P into forms relatively unavailable to the soil test extractants within the six week incubation period. Unlike in the incubated soils for the runoff study or for the other extract methods, the soil x fertility treatment interaction was not significant for Olsen extractable P. In both soils, application of MAP and liquid swine manure produced significantly higher Olsen P concentrations than for solid cattle manure treated and un-amended soils.

Overall, the amounts of soil P extracted after incubation with different soil test P methods after incubation were similar in corresponding treatments for the leaching and runoff studies (Appendix 9 and 17). In Lone sand, MAP and liquid swine manure treated soils, in general, showed significantly higher soil test P than solid cattle manure treated and unamended soils in both runoff and leaching studies. In Newdale CL, the differences among treatments were not statistically significant (Table 15), while the corresponding treatments of the runoff study showed significant differences (Table 11).

3.5.5. Relationships between SRP loss and Soil test P

In Lone Sand, P extracted by Mehlich 3, modified Kelowna, Olsen and water predicted total SRP loss well, explaining 61-67% of total variation (Figure 14, Table 16). In Newdale CL, however, the correlation coefficients between Mehlich 3-P, modified Kelowna-P and Olsen-P with SRP loss were low, even though they were statistically significant. Only water extractable P showed a highly significant correlation with SRP loss in this soil, explaining 54% of the variation. When correlation analysis was conducted combining results of both soils, water extractable P proved to be the best method to predict P loss (Table 16).

Table 14. Correlation coefficients (r) between SRP loss during 3.5 pore volume of elution and P fractions in manure

Manure P fraction	Correlation coefficient (r)	
	Lone Sand	Newdale CL
Water-P_i	0.15 ^{NS}	0.40 ^{NS}
$NaHCO_3$ -P_i	0.17 ^{NS}	-0.01 ^{NS}
Labile P_i (Water-P_i + $NaHCO_3$- P_i)	0.20 ^{NS}	0.13 ^{NS}
NaOH -P_i	0.69 *	0.07 ^{NS}
HCl -P_i	-0.11 ^{NS}	0.36 ^{NS}
Total inorganic P	0.49 ^{NS}	0.2 ^{NS}
Water -P_t	0.19 ^{NS}	0.44 ^{NS}
$NaHCO_3$ -P_t	0.50 ^{NS}	-0.07 ^{NS}
Labile -P_t (Water-P_t + $NaHCO_3$- P_t)	0.50 ^{NS}	0.11 ^{NS}
NaOH- P_t	0.26 ^{NS}	-0.21 ^{NS}
HCl- P_t	-0.23 ^{NS}	0.26 ^{NS}
Residual P	-0.63 ^{NS}	-0.37 ^{NS}
Total P	0.11 ^{NS}	-0.08 ^{NS}

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; ^{NS} indicates not significant at p = 0.05

Table 15. Least square means[1] of soil P extracted (mg kg^{-1}) by different STP methods in leaching study

Effect	P extracted by different STP methods[2] (mg kg^{-1})			
	Mehlich 3[3]	Modified Kelowna[3]	Olsen	Water[3]
Soil				
Lone Sand			31.9 a	
Newdale CL			35.9 a	
Fertility treatment				
Liquid swine manure			42.3 a	
Solid cattle manure			29.6 b	
MAP			42.6 a	
Check			21.2 b	
Soil x Fertility Trt.				
Lone Sand				
Liquid swine manure	72.6 a	57.5 a		17.3 a
Solid cattle manure	40.9 b	29.4 b		6.1 b
MAP	67.8 a	52.8 a		15.6 a
Check	27.5 b	19.4 b		3.7 b
Newdale CL				
Liquid swine manure	60.5 a	38.6 a		8.0 a
Solid cattle manure	54.4 a	33.2 a		6.8 a
MAP	72.8 a	39.9 a		11.6 a
Check	44.0 a	18.6 a		5.2 a
ANOVA	**P>F**			
Soil	**0.1776**	**0.0519**	**<0.1694**	**0.0163**
Fertility treatment	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Soil x Fert. Trt	**0.0083**	**0.0095**	**0.1041**	**0.0002**

[1] Least square means computed using Proc Mixed (SAS version 9.1) for two-way ANOVA considering different sources of manure as replicates; 2 soils, 4 fertility treatments (8 replicates for fertility treatments 1 and 2 and 2 replicates for fertility treatments 3 and 4).
[2] Means within the same column followed by the same lower case letter are not significantly different at $p \leq 0.05$ by Tukey-Kramer test.
[3] Mean separation for main effects not shown since the interaction was significant ($p \leq 0.05$).

Table 16. Relationships between soil test P and SRP loss with the elution of 3.5 pore volumes of water

	Mehlich 3-P	Modified Kelowna-P	Olsen-P	Water extr. P
Lone Sand (n=20)	0.82 ***	0.81 ***	0.80 ***	0.78 ***
Newdale CL (n=20)	0.56 **	0.44 *	0.46 *	0.73 ***
Both soils (n=40)	0.58 ***	0.74 ***	0.51 ***	0.80 ***

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at p = 0.05

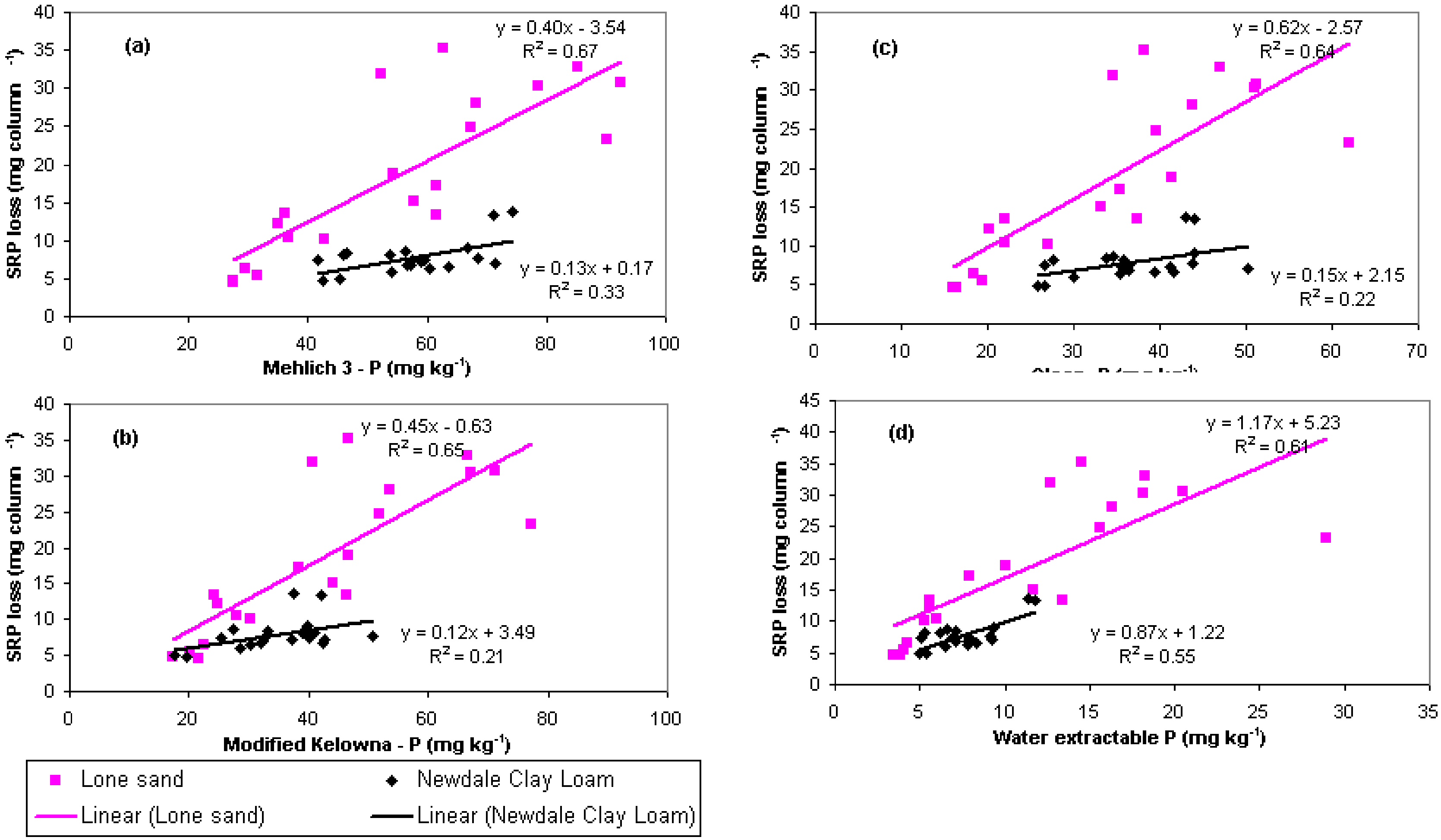


Figure 14 **Relationship between Soil test P and SRP leaching loss (a) Mehlich 3-P (b) modified Kelowna P (c) Olsen P and (d) water extractable P**

CONCLUSIONS

Liquid swine manure had a higher total P on dry weight basis as well as a higher proportion of labile P (water-P_t + $NaHCO_3$-P_t) than solid cattle manure. With Lone Sand, runoff and leaching losses of SRP in the runoff study with high intensity rainfall and in the column study with low intensity rainfall were greater from liquid swine manure treated soils than from solid cattle manure treated soils. The same trend was observed for runoff SRP loss in Newdale CL, but in the leaching column study, SRP losses were similar from both liquid swine manure and solid cattle manure treated Newdale CL. This is very likely due to the interaction of P with soil during the slow leaching and the greater ability of Newdale CL to retain P. In both soils, SRP runoff and leaching losses from the MAP treatment were similar to or even greater than that of liquid swine manure treatments.

The environmental availability of P in liquid swine manure was generally greater than that in solid cattle manure, but less than in MAP. Water-P_i and water-P_t fractions in manure did not show a significant correlation with runoff or leaching SRP loss. Conversely, $NaHCO_3$–P_i , $NaHCO_3$-P_t and labile P_t fractions in manure showed highly significant correlations with runoff and percolate losses under high intensity rainfall. The equations between SRP loss and labile-P_t fraction in manure were stable for the two soils, indicating that the same equation could be used to predict P loss from labile - P_t. Olsen P predicted the runoff losses of SRP better than Mehlich 3, modified Kelowna and water extractable P when both soils were considered, while water extractable P was better in predicting leaching losses of SRP.

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Appendices

Appendix 1- Runoff and percolate volumes (L/tray) in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff volume (L)		Percolate volume (L)	Runoff volume (L)		Percolate volume (L)
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	10.6	14.2	1.7	15.0	16.5	1.1
	2	13.3	14.8	4.1	16.6	16.2	0.3
SM2	**1**	11.8	13.8	3.8	15.2	14.4	0.1
	2	11.1	12.6	1.1	13.9	14.1	0.3
SM3	**1**	10.1	11.9	1.8	15.2	16.7	0.2
	2	14.6	15.3	1.8	19.6	20.0	0.3
SM4	**1**	10.5	11.5	3.4	10.0	5.5	2.2
	2	11.1	12.2	2.9	13.2	16.1	2.3
CM1	**1**	16.1	11.5	3.1	12.8	13.5	1.0
	2	11.9	13.1	3.2	14.9	16.2	0.3
CM2	**1**	15.1	14.7	1.4	16.3	17.6	0.1
	2	18.8	18.8	1.7	12.8	13.5	1.0
CM3	**1**	11.5	11.3	3.6	19.1	19.9	0.7
	2	14.5	17.8	1.6	18.4	21.0	0.8
CM4	**1**	14.2	16.1	3.8	11.1	12.0	0.3
	2	14.3	15.5	1.7	19.1	19.9	0.7
MAP	**1**	12.7	13.9	0.4	16.7	17.6	0.2
	2	11.9	9.3	8.1	20.4	21.5	0.4
Check	**1**	9.8	12.0	3.4	9.7	10.6	0.4
	2	12.1	13.2	2.9	13.2	13.9	0.3
Average		**12.8**	**13.7**	**2.79**	**15.2**	**15.8**	**0.6**
SD		**2.3**	**2.3**	**1.64**	**3.2**	**3.9**	**0.6**

Appendix 2- Total sediments (kg/tray) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	17.2	14.2	2.7	283.6	132.4	3.9
	2	16.2	16.7	5.7	225.7	296.0	0.1
SM2	**1**	20.6	10.7	3.3	92.7	140.3	0.1
	2	23.8	20.8	2.0	203.8	150.5	0.7
SM3	**1**	26.4	24.8	1.8	181.0	99.5	0.1
	2	34.0	28.3	2.3	308.5	337.2	0.1
SM4	**1**	26.0	41.3	2.4	119.1	47.0	3.0
	2	38.3	36.0	2.4	137.8	213.8	5.6
CM1	**1**	31.1	9.3	2.7	128.0	246.6	1.5
	2	39.3	28.0	2.0	119.4	191.4	0.1
CM2	**1**	31.9	16.1	1.0	286.6	317.2	0.1
	2	28.5	29.3	1.2	127.5	213.5	0.6
CM3	**1**	21.0	12.4	8.5	585.7	153.4	0.4
	2	28.8	25.5	1.2	186.2	294.3	0.0
CM4	**1**	36.2	24.5	0.9	108.6	117.0	0.1
	2	37.8	34.3	0.7	309.2	450.7	0.3
MAP	**1**	6.1	6.8	0.2	206.6	215.0	0.2
	2	21.2	8.9	3.3	416.7	233.9	0.2
Check	**1**	54.7	52.3	2.7	121.4	120.3	0.4
	2	59.9	40.7	1.6	228.4	203.2	0.2
Average		**30.0**	**24.0**	**2.43**	**218.8**	**208.7**	**0.9**
SD		**12.6**	**12.5**	**1.86**	**121.9**	**96.1**	**1.5**

Appendix 3- Soluble reactive phosphorus (SRP) concentrations (mg L^{-1}) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	0.51	0.21	8.33	0.70	0.41	0.39
	2	0.40	0.33	6.73	0.68	0.70	0.34
SM2	**1**	0.66	0.36	3.06	0.34	0.47	0.24
	2	0.70	0.38	6.43	0.49	0.53	0.37
SM3	**1**	0.69	0.38	7.41	0.40	0.37	0.56
	2	0.70	0.40	6.92	0.39	0.48	0.20
SM4	**1**	0.89	0.49	1.62	0.65	0.65	0.87
	2	0.87	0.59	1.41	0.45	0.57	0.87
CM1	**1**	0.32	0.14	1.43	0.37	0.46	0.48
	2	0.41	0.25	0.82	0.35	0.42	0.36
CM2	**1**	0.54	0.27	5.28	0.42	0.41	0.28
	2	0.40	0.29	1.94	0.26	0.31	0.57
CM3	**1**	0.58	0.33	4.30	0.54	0.39	0.85
	2	0.53	0.43	5.67	0.47	0.39	0.14
CM4	**1**	0.36	0.12	0.64	0.25	0.24	0.51
	2	0.22	0.14	0.88	0.24	0.29	0.35
MAP	**1**	0.59	0.26	3.78	0.79	0.83	0.90
	2	0.69	0.32	0.48	0.79	0.69	1.41
Check	**1**	0.16	0.11	0.55	0.33	0.31	0.40
	2	0.23	0.13	0.40	0.25	0.24	0.24

Appendix 4- Soluble reactive phosphorus load (mg tray^{-1}) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	5.47	3.02	14.34	10.48	6.84	0.42
	2	5.33	4.87	14.36	10.02	11.30	0.09
SM2	**1**	7.80	4.97	11.65	5.22	6.75	0.03
	2	7.78	4.80	7.25	6.85	7.48	0.10
SM3	**1**	6.93	4.57	13.29	6.02	6.20	0.10
	2	10.22	6.12	12.22	7.66	9.60	0.06
SM4	**1**	9.31	5.62	5.49	6.55	3.55	1.86
	2	9.63	7.25	4.11	5.93	9.18	1.97
CM1	**1**	5.11	1.59	4.48	4.70	6.23	0.47
	2	4.88	3.28	2.64	5.23	6.83	0.11
CM2	**1**	8.13	3.98	7.36	6.89	7.13	0.03
	2	7.50	5.47	3.39	3.38	4.17	0.56
CM3	**1**	8.42	4.71	8.32	10.24	7.73	0.61
	2	7.66	7.44	9.33	8.72	8.13	0.12
CM4	**1**	5.11	1.93	2.43	2.79	2.95	0.17
	2	3.15	2.18	1.50	4.63	5.85	0.25
MAP	**1**	7.48	3.57	1.63	13.11	14.67	0.22
	2	8.20	2.95	3.92	11.35	10.70	0.50
Check	**1**	1.56	1.36	1.24	3.21	3.23	0.14
	2	2.76	1.76	0.92	3.23	3.28	0.08

Appendix 5- Total dissolved phosphorus (TDP) concentrations (mg L^{-1}) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	0.53	0.23	9.22	0.76	0.43	0.41
	2	0.46	0.38	7.59	0.71	0.73	0.35
SM2	**1**	0.72	0.37	3.34	0.34	0.48	0.26
	2	0.73	0.40	6.91	0.52	0.53	0.40
SM3	**1**	0.73	0.40	7.78	0.41	0.40	0.58
	2	0.77	0.44	7.06	0.41	0.50	0.22
SM4	**1**	0.90	0.53	1.81	0.65	0.66	0.92
	2	0.87	0.66	1.59	0.52	0.59	0.90
CM1	**1**	0.34	0.16	1.57	0.40	0.51	0.53
	2	0.44	0.26	0.91	0.38	0.44	0.39
CM2	**1**	0.60	0.31	5.56	0.44	0.42	0.31
	2	0.42	0.31	2.17	0.27	0.32	0.63
CM3	**1**	0.64	0.34	2.21	0.56	0.42	0.96
	2	0.59	0.48	6.48	0.50	0.40	0.15
CM4	**1**	0.42	0.14	0.74	0.26	0.25	0.55
	2	0.24	0.15	0.90	0.26	0.31	0.38
MAP	**1**	0.63	0.28	3.81	0.79	0.87	0.95
	2	0.73	0.33	0.53	0.81	0.73	1.43
Check	**1**	0.18	0.12	0.60	0.33	0.31	0.44
	2	0.25	0.14	0.41	0.28	0.24	0.27

Appendix 6- Total dissolved phosphorus (TDP) load (mg tray^{-1}) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	5.69	3.27	15.88	11.35	7.09	0.44
	2	6.11	5.64	16.20	10.38	11.81	0.09
SM2	**1**	8.45	5.14	12.74	5.24	6.90	0.03
	2	8.08	5.06	7.80	7.15	7.53	0.11
SM3	**1**	7.33	4.78	13.96	6.24	6.71	0.11
	2	11.20	6.72	12.47	8.06	9.94	0.06
SM4	**1**	9.47	6.18	6.14	6.51	3.60	1.99
	2	9.62	8.06	4.63	6.79	9.56	2.06
CM1	**1**	5.54	1.84	4.92	5.13	6.82	0.52
	2	5.22	3.40	2.95	5.68	7.11	0.12
CM2	**1**	9.07	4.52	7.76	7.16	7.40	0.04
	2	7.88	5.77	3.79	3.44	4.25	0.61
CM3	**1**	9.30	4.91	4.59	10.79	8.35	0.69
	2	8.56	8.49	10.66	9.15	8.42	0.13
CM4	**1**	5.98	2.25	2.80	2.87	3.01	0.19
	2	3.44	2.33	1.54	4.96	6.09	0.27
MAP	**1**	8.01	3.85	1.64	13.14	15.22	0.24
	2	8.65	3.02	4.27	11.58	11.33	0.51
Check	**1**	1.76	1.44	1.37	3.24	3.24	0.15
	2	3.02	1.85	0.94	3.66	3.34	0.09

Appendix 7- Total phosphorus (TP) concentrations (mg L^{-1}) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand			Newdale CL		
		Runoff		Percolate	Runoff		Percolate
		0-30 min	30-60 min		0-30 min	30-60 min	
SM1	**1**	4.33	2.86	10.10	29.95	11.05	8.34
	2	4.08	4.12	8.36	18.21	17.83	1.75
SM2	**1**	5.41	4.23	3.57	9.00	12.70	1.15
	2	7.07	5.44	7.24	19.10	15.67	5.01
SM3	**1**	5.42	3.87	8.55	13.85	7.55	1.09
	2	8.62	5.16	8.56	17.10	15.70	1.68
SM4	**1**	7.65	5.55	2.60	14.00	11.65	2.70
	2	9.15	4.80	6.67	10.85	13.85	5.31
CM1	**1**	4.78	1.95	2.30	13.10	22.20	1.89
	2	8.76	5.64	2.21	10.05	12.60	0.95
CM2	**1**	4.50	2.45	5.59	20.20	17.20	2.21
	2	6.45	4.78	2.89	6.35	14.25	1.85
CM3	**1**	4.21	2.42	8.72	35.65	11.90	1.95
	2	3.93	2.06	6.89	11.46	11.08	2.50
CM4	**1**	5.18	4.46	1.53	10.75	11.05	1.79
	2	6.77	4.51	1.88	14.40	14.95	1.63
MAP	**1**	4.92	3.15	4.28	14.35	14.25	1.99
	2	9.64	4.30	2.98	19.70	12.90	9.56
Check	**1**	4.85	4.95	1.36	15.25	15.35	1.09
	2	8.95	4.35	1.29	18.20	16.85	1.20

Appendix 8- Total phosphorus (TP) load (mg $tray^{-1}$) in runoff and percolate in different fertility treatments and replicates for Lone Sand and Newdale CL

Fertility Treatment	Replicate	Lone Sand Runoff 0-30 min	Lone Sand Runoff 30-60 min	Lone Sand Percolate	Newdale CL Runoff 0-30 min	Newdale CL Runoff 30-60 min	Newdale CL Percolate
SM1	**1**	46.10	40.53	17.39	448.47	182.39	8.99
	2	54.38	60.82	17.84	266.61	289.08	0.46
SM2	**1**	63.62	58.41	13.62	137.14	183.44	0.14
	2	78.43	68.66	8.17	264.76	220.40	1.33
SM3	**1**	54.57	46.12	15.34	210.35	126.33	0.20
	2	125.82	78.90	15.12	335.81	314.13	0.48
SM4	**1**	80.06	64.08	8.82	140.11	63.54	5.81
	2	101.71	58.60	19.40	142.85	223.43	12.10
CM1	**1**	77.01	22.40	7.21	167.63	298.99	1.84
	2	104.17	74.09	7.12	149.28	203.89	0.28
CM2	**1**	67.79	36.11	7.79	329.38	302.79	0.27
	2	120.94	90.09	5.05	81.25	191.92	1.80
CM3	**1**	61.11	34.50	18.09	681.98	236.41	1.39
	2	56.79	36.62	11.34	211.06	232.59	2.09
CM4	**1**	73.67	71.62	5.81	118.87	133.13	0.60
	2	96.93	70.09	3.20	275.47	297.00	1.16
MAP	**1**	62.39	43.67	1.84	239.56	250.54	0.49
	2	114.54	39.88	24.21	282.93	200.57	3.40
Check	**1**	47.49	59.23	3.09	147.77	162.31	0.38
	2	108.04	57.52	2.95	239.91	234.32	0.39

Appendix 9- Soil test P (mg kg^{-1}) in incubated soils prior to runoff

Soil	Fertility Treatment	Replicate	P extracted (mg kg^{-1})			
			Mehlich 3	Modified Kelowna	Olsen	Water
Lone Sand	**SM1**	**1**	71.0	53.9	44.4	18.8
		2	71.3	55.9	46.1	20.0
	SM2	**1**	73.6	56.6	44.0	21.8
		2	69.4	56.4	45.0	19.9
	SM3	**1**	68.7	53.1	45.2	19.5
		2	65.7	54.3	46.1	18.4
	SM4	**1**	59.9	46.6	35.7	9.1
		2	68.8	45.9	43.9	9.7
	CM1	**1**	39.3	30.1	24.8	7.3
		2	42.6	30.3	24.6	7.1
	CM2	**1**	55.4	46.3	37.5	13.5
		2	40.6	30.7	24.7	8.1
	CM3	**1**	40.6	30.0	24.5	7.3
		2	52.7	41.0	33.7	11.7
	CM4	**1**	35.0	21.8	21.3	5.9
		2	36.2	25.6	22.8	6.2
	MAP	**1**	77.1	59.3	45.5	21.4
		2	69.6	50.3	45.0	18.8
	Check	**1**	31.8	19.4	18.5	4.0
		2	35.6	20.9	20.6	4.5
Newdale CL	**SM1**	**1**	65.1	46.1	43.8	7.9
		2	68.7	50.9	47.8	9.0
	SM2	**1**	59.0	41.9	36.9	6.5
		2	69.4	51.2	44.4	10.6
	SM3	**1**	80.7	61.7	54.4	14.5
		2	66.0	49.4	43.6	8.4
	SM4	**1**	52.9	38.5	38.0	6.2
		2	48.4	35.0	34.4	5.6
	CM1	**1**	50.0	36.1	38.3	6.3
		2	49.4	35.5	33.1	6.1
	CM2	**1**	54.6	38.8	37.4	7.5
		2	54.4	37.2	35.2	6.7
	CM3	**1**	49.0	38.4	31.0	8.6
		2	52.7	41.0	33.7	10.6
	CM4	**1**	49.5	32.1	31.0	5.4
		2	43.1	31.4	31.4	5.6
	MAP	**1**	94.2	69.7	64.3	11.5
		2	84.7	62.1	62.2	12.4
	Check	**1**	48.9	34.2	33.1	6.2
		2	35.7	25.2	25.9	3.6

Appendix 10- Regression equations between P extracted from different STP and P loss for Lone Sand (n=40)

X variable	Y variable	Slope	Intercept	r	P > F
Mehlich 3-P	**Runoff SRP conc. 0-30 min**	0.0086	-0.0057	0.68	***
	Runoff SRP conc. 30-60 min	0.0068	0.0131	0.63	**
	Percolate SRP conc.			0.29	NS
	Runoff SRP load 0-30 min	0.1133	0.2547	0.65	**
	Runoff SRP load 30-60 min	0.1082	0.5904	0.57	*
	Percolate SRP load 0-60 min			0.22	NS
	Total runoff SRP load 0-60 min	0.2214	2.5403	0.66	**
	Total SRP removed	0.2860	-0.5700	0.66	***
	SRP loss as a % of added P	0.0306	-0.8135	0.67	**
Modified Kelowna –P	**Runoff SRP conc. 0-30 min**	0.0107	0.0382	0.70	***
	Runoff SRP conc. 30-60 min	0.0078	0.0492	0.59	**
	Percolate SRP conc.	0.0771	-1.2856	0.40	*
	Runoff SRP load 0-30 min	0.1432	0.6833	0.68	**
	Runoff SRP load 30-60 min	0.1264	0.2580	0.55	*
	Percolate SRP load 0-60 min	0.1124	-1.2890	0.32	*
	Total runoff SRP load 0-60 min	0.2696	0.9414	0.66	**
	Total SRP removed	0.3820	0.3476	0.72	***
	SRP loss as a % of added P	0.0398	-0.4608	0.72	***
Olsen P	**Runoff SRP conc. 0-30 min**	0.0119	0.0458	0.66	***
	Runoff SRP conc. 30-60 min	0.0110	0.0318	0.71	**
	Percolate SRP conc.			0.24	NS
	Runoff SRP load 0-30 min	0.1620	0.6651	0.65	**
	Runoff SRP load 30-60 min	0.1732	0.8870	0.64	*
	Percolate SRP load 0-60 min			0.14	NS
	Total runoff SRP load 0-60 min	0.3352	2.7088	0.70	**
	Total SRP removed	0.3957	0.9646	0.64	***
	SRP loss as a % of added P	0.0429	-0.6712	0.66	***
Water extractable P	**Runoff SRP conc. 0-30 min**	0.0191	0.2943	0.53	*
	Runoff SRP conc. 30-60 min			0.07	NS
	Percolate SRP conc.	0.3224	-1.3563	0.72	***
	Runoff SRP load 0-30 min	0.1996	4.6627	0.41	*
	Runoff SRP load 30-60 min			0.04	NS
	Percolate SRP load 0-60 min	0.5713	0.4410	0.69	**
	Total runoff SRP load 0-60 min			0.23	NS
	Total SRP removed	0.7929	7.5841	0.65	**
	SRP loss as a % of added P	0.0804	0.1027	0.63	**

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at p = 0.05

Appendix 11- Regression equations between P extracted from different STP and P loss for Newdale CL (n=20)

X variable	Y variable	Slope	Intercept	r	p > F
Mehlich 3-P	**Runoff SRP conc. 0-30 min**	0.0084	-0.0349	0.70	***
	Runoff SRP conc. 30-60 min	0.0076	0.0101	0.69	***
	Percolate SRP conc.			0.42	NS
	Runoff SRP load 0-30 min	0.1417	-1.5237	0.70	***
	Runoff SRP load 30-60 min	0.1442	-1.3898	0.71	***
	Percolate SRP load 0-60 min			-0.17	NS
	Total runoff SRP load 0-60 min	0.2858	-2.9135	0.74	***
	Total SRP removed	0.2794	-2.1403	0.72	***
	SRP loss as a % of added P	0.0345	-1.2777	0.79	***
Modified Kelowna –P	**Runoff SRP conc. 0-30 min**	0.0109	-0.0102	0.71	***
	Runoff SRP conc. 30-60 min	0.0099	0.0358	0.70	***
	Percolate SRP conc.			0.41	NS
	Runoff SRP load 0-30 min	0.1918	-1.4025	0.74	***
	Runoff SRP load 30-60 min	0.1932	-1.1855	0.74	***
	Percolate SRP load 0-60 min			-0.17	NS
	Total runoff SRP load 0-60 min	0.3851	-2.5880	0.77	***
	Total SRP removed	0.3771	-1.8532	0.76	***
	SRP loss as a % of added P	0.0450	-1.1748	0.81	***
Olsen P	**Runoff SRP conc. 0-30 min**	0.0126	-0.0447	0.73	***
	Runoff SRP conc. 30-60 min	0.0116	-0.0060	0.74	***
	Percolate SRP conc.	0.0153	-0.0942	0.50	*
	Runoff SRP load 0-30 min	0.2020	-1.2672	0.70	***
	Runoff SRP load 30-60 min	0.2072	-1.1960	0.72	***
	Percolate SRP load 0-60 min			-0.09	NS
	Total runoff SRP load 0-60 min	0.4091	-2.4632	0.74	***
	Total SRP removed	0.4042	-1.8699	0.73	***
	SRP loss as a % of added P	0.0516	-1.3114	0.83	***
Water extractable P	**Runoff SRP conc. 0-30 min**	0.0366	0.1676	0.56	*
	Runoff SRP conc. 30-60 min	0.0266	0.2460	0.45	*
	Percolate SRP conc.			0.32	NS
	Runoff SRP load 0-30 min	0.7050	1.2062	0.65	**
	Runoff SRP load 30-60 min	0.6322	2.0621	0.58	**
	Percolate SRP load 0-60 min			-0.23	NS
	Total runoff SRP load 0-60 min	1.3372	3.2673	0.64	**
	Total SRP removed	1.2918	4.0233	0.62	**
	SRP loss as a % of added P	0.1381	-0.3486	0.59	**

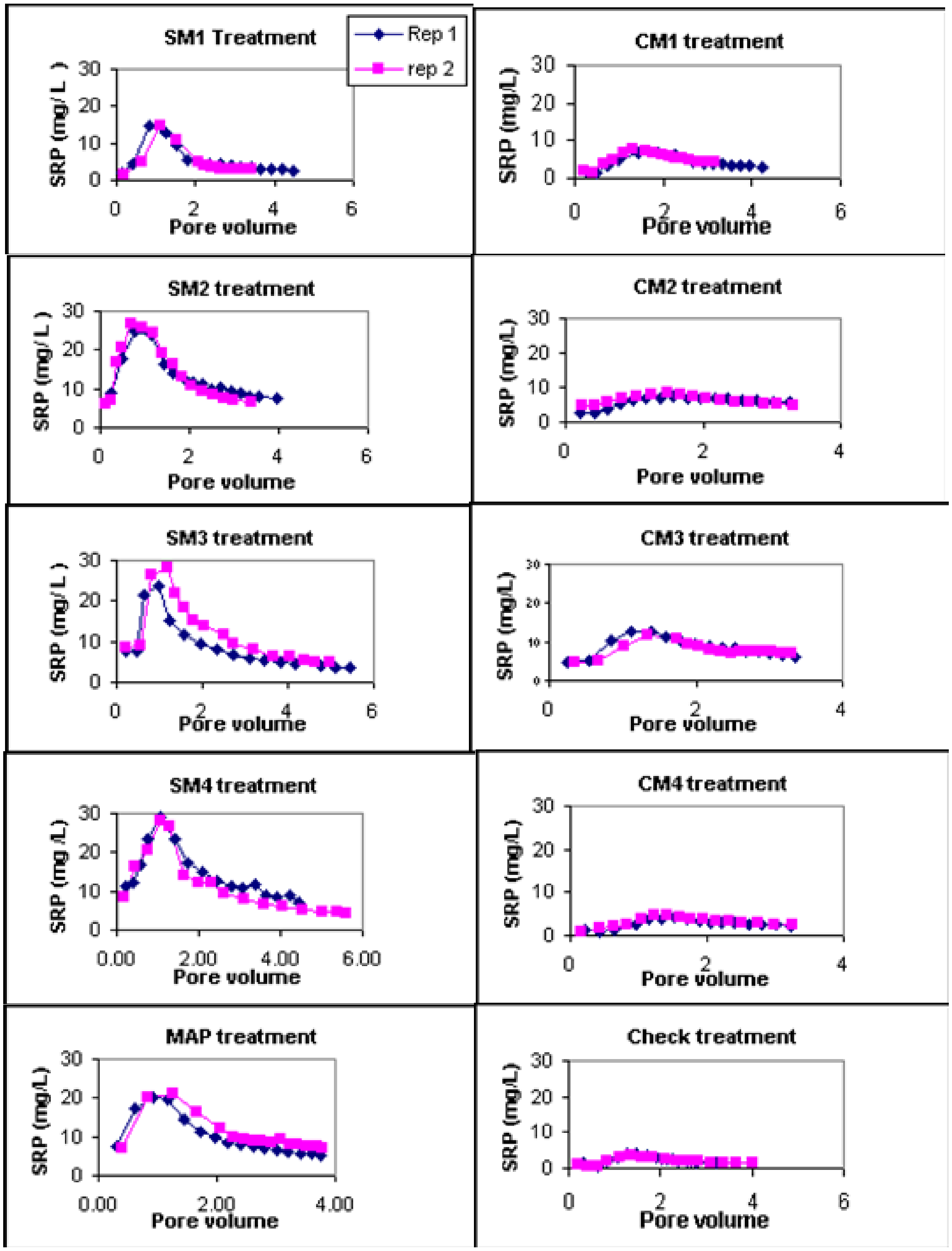
***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; NS indicates not significant at p = 0.05

Appendix 12- Regression equations between P extracted from different STP and P loss for both soils (n=40)

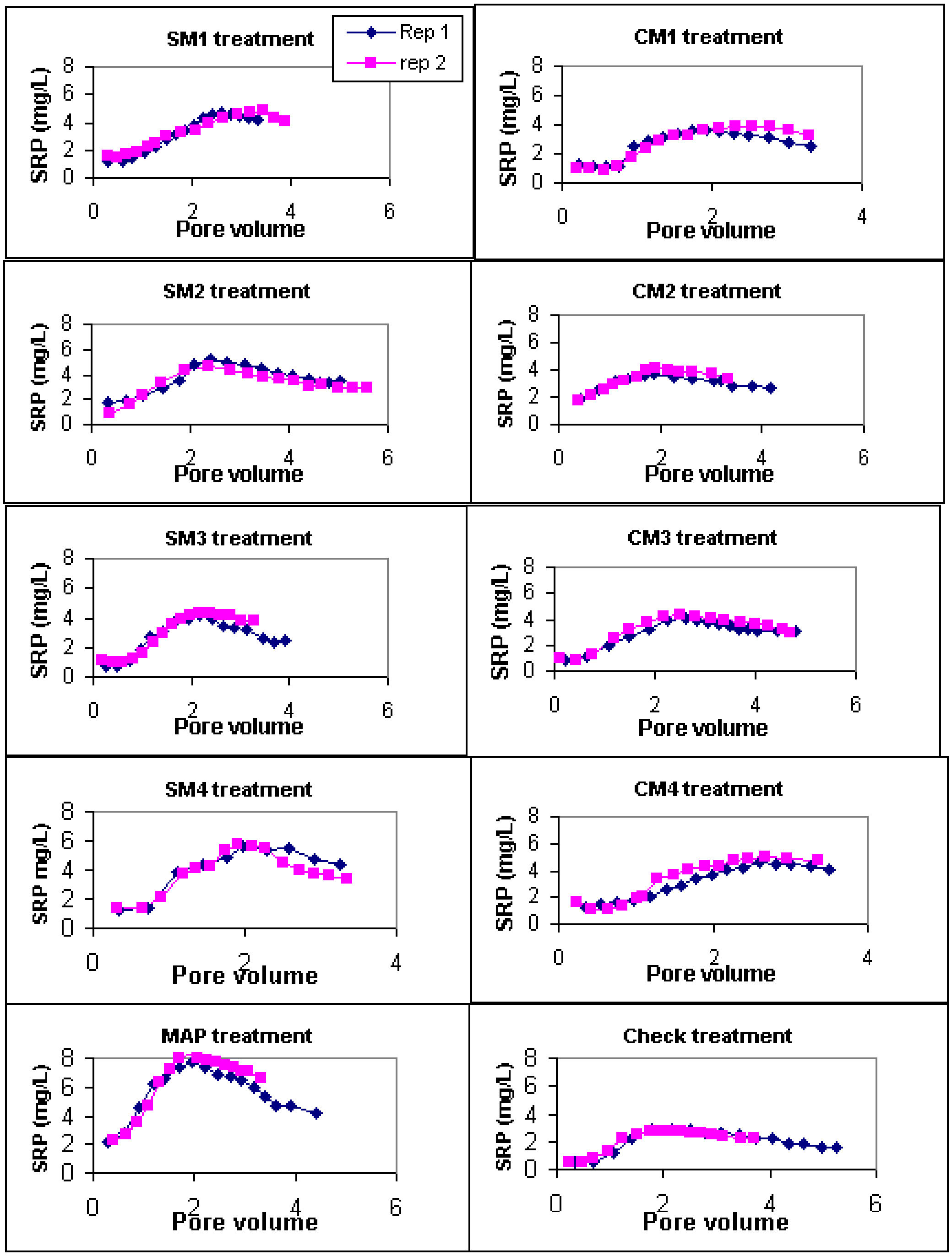
X variable	Y variable	Slope	Intercept	r	P > F
Mehlich 3-P	**Runoff SRP conc. 0-30 min**	0.0086	-0.0057	0.68	***
	Runoff SRP conc. 30-60 min	0.0068	-0.0131	0.63	***
	Percolate SRP conc.			0.29	NS
	Runoff SRP load 0-30 min	0.1133	0.2547	0.65	***
	Runoff SRP load 30-60 min	0.1082	-0.5904	0.57	***
	Percolate SRP load 0-60 min			0.22	NS
	Total runoff SRP load 0-60 min	0.2214	-0.3358	0.66	***
	Total SRP removed	0.2860	-0.5700	0.66	***
	SRP loss as a % of added P	0.0306	-0.8135	0.67	***
Modified Kelowna –P	**Runoff SRP conc. 0-30 min**	0.0107	0.0382	0.70	***
	Runoff SRP conc. 30-60 min	0.0078	0.0492	0.59	***
	Percolate SRP conc.	0.0771	-1.2856	0.40	*
	Runoff SRP load 0-30 min	0.1432	0.6833	0.68	***
	Runoff SRP load 30-60 min	0.1264	0.2580	0.55	***
	Percolate SRP load 0-60 min	0.1124	-1.2890	0.32	*
	Total runoff SRP load 0-60 min	0.2696	0.9414	0.66	***
	Total SRP removed	0.3820	-0.3476	0.72	***
	SRP loss as a % of added P	0.0398	-0.7487.	0.72	***
Olsen P	**Runoff SRP conc. 0-30 min**	0.0119	0.0458	0.66	***
	Runoff SRP conc. 30-60 min	0.0110	-0.0318	0.71	***
	Percolate SRP conc.			0.24	NS
	Runoff SRP load 0-30 min	0.1620	0.6651	0.65	***
	Runoff SRP load 30-60 min	0.1732	-0.8870	0.64	***
	Percolate SRP load 0-60 min			0.14	NS
	Total runoff SRP load 0-60 min	0.3352	-0.2220	0.70	***
	Total SRP removed	0.3957	0.9646	0.64	***
	SRP loss as a % of added P	0.0429	-0.6712	0.66	***
Water extractable P	**Runoff SRP conc. 0-30 min**	0.0191	0.2943	0.53	***
	Runoff SRP conc. 30-60 min			0.07	NS
	Percolate SRP conc.	0.3224	-1.3563	0.72	***
	Runoff SRP load 0-30 min	0.1996	4.6627	0.41	*
	Runoff SRP load 30-60 min			0.04	NS
	Percolate SRP load 0-60 min	0.5713	-2.4329	0.69	***
	Total runoff SRP load 0-60 min			0.23	NS
	Total SRP removed	0.7929	7.5841	0.65	***
	SRP loss as a % of added P	0.0804	0.1027	0.63	***

***, **, * indicate significance at 0.001, 0.01 and 0.05 probability, respectively; [NS] indicates not significant at p = 0.05

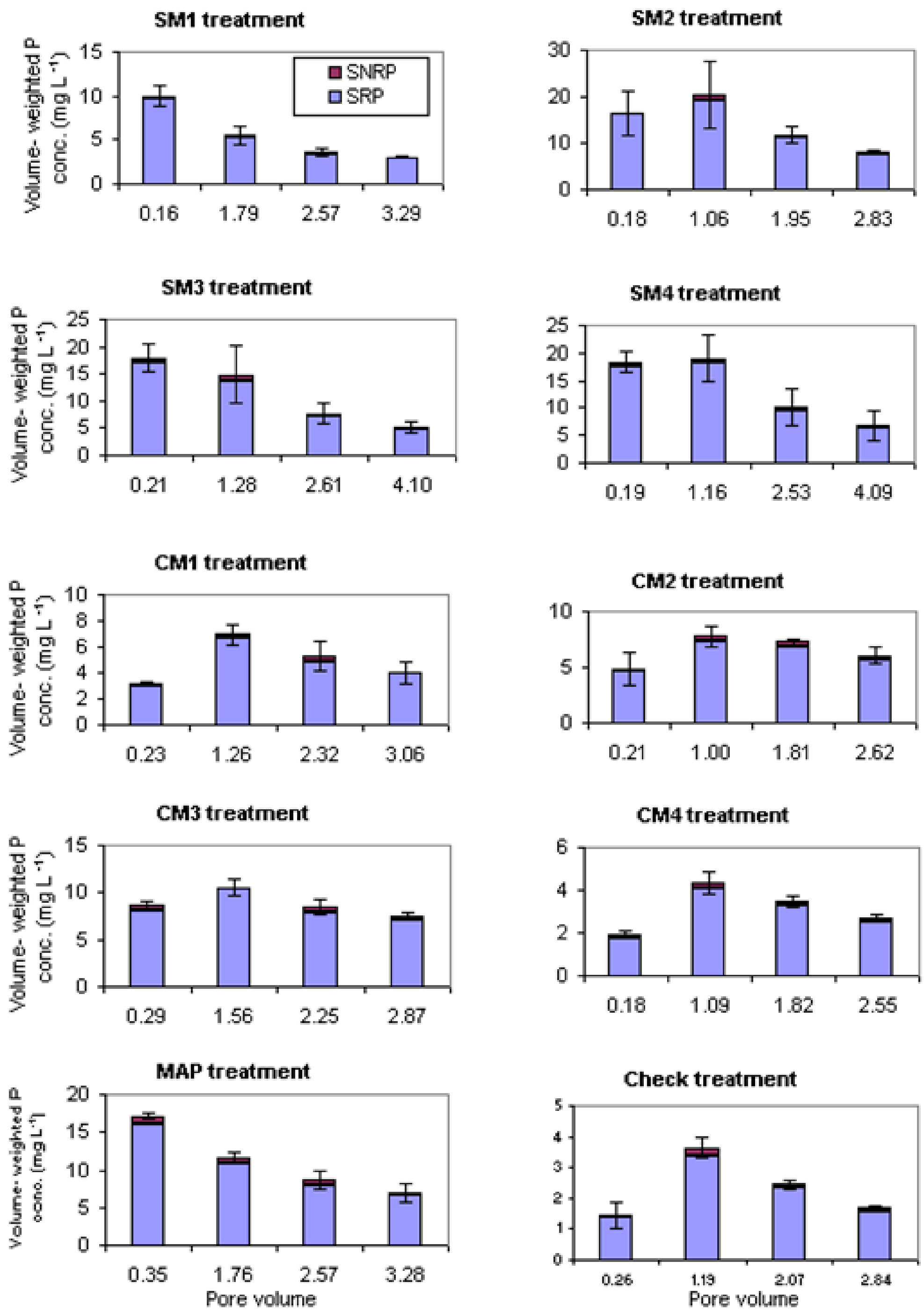
Appendix 13 - Breakthrough curves for different fertility treatments in Lone Sand



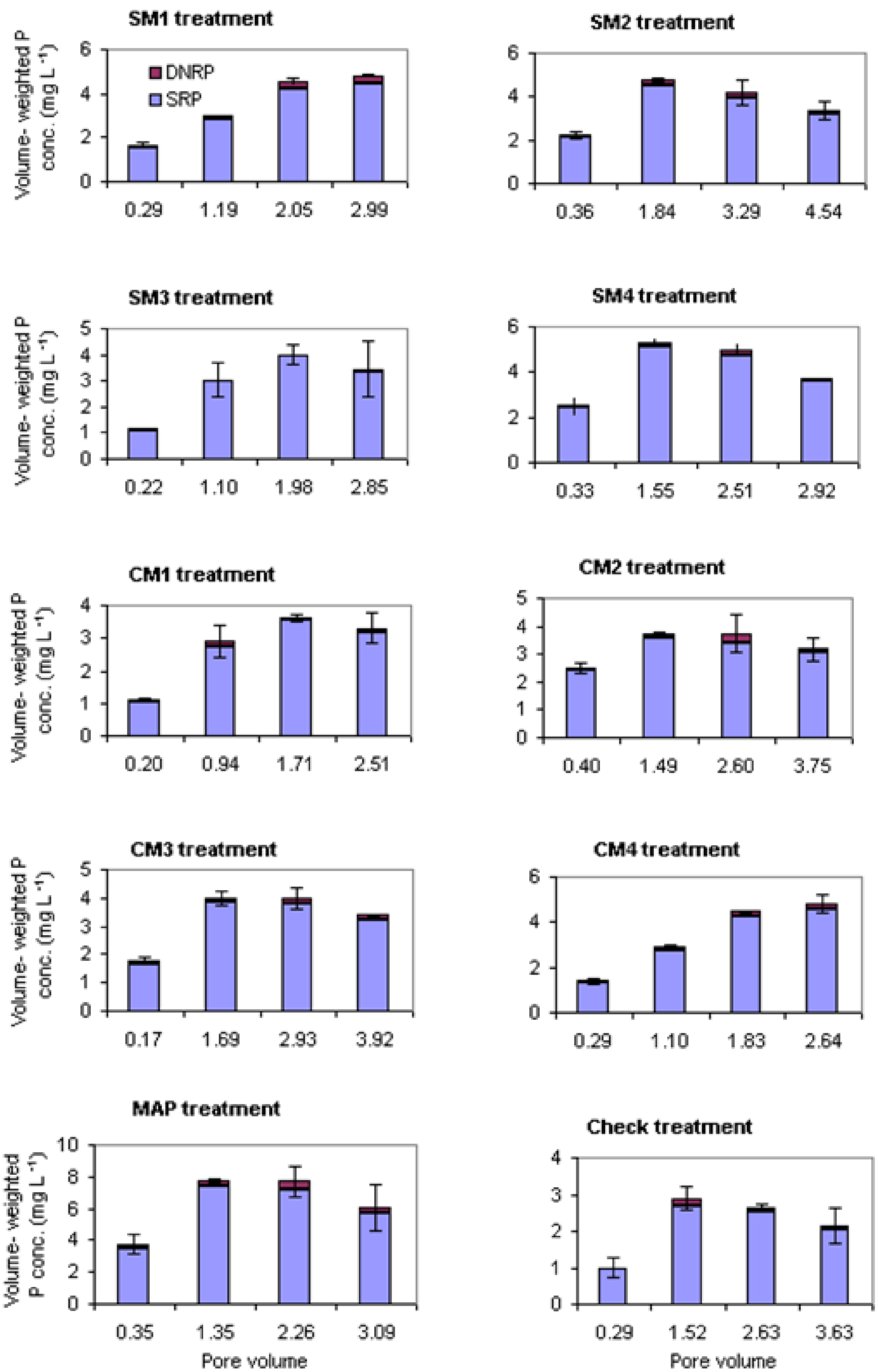
Appendix 14 - Breakthrough curves for different fertility treatments in Newdale CL



Appendix 15. Volume weighted concentration of SRP and SNRP in leachate samples in different fertility treatments of Lone Sand



Appendix 16. Volume weighted concentration of SRP and SNRP in leachate samples in different fertility treatments of Newdale CL



Appendix 17- Soil test P (mg kg^{-1}) in incubated soils prior to leaching

Soil	Fertility Treatment	Replicate	P extracted (mg kg^{-1})			
			Mehlich 3	Modified Kelowna	Olsen	Water
Lone Sand	**SM1**	**1**	57.8	44.1	33.1	11.7
		2	61.6	46.5	37.3	13.4
	SM2	**1**	92.6	71.2	51.1	20.5
		2	78.6	67.1	50.9	18.2
	SM3	**1**	90.1	77.1	62.0	28.9
		2	85.3	66.5	46.9	18.3
	SM4	**1**	62.6	46.8	38.1	14.6
		2	52.2	40.6	34.6	12.7
	CM1	**1**	42.7	30.2	27.0	5.3
		2	36.8	28.0	21.9	6.0
	CM2	**1**	34.9	24.7	20.1	5.6
		2	36.2	24.3	21.9	5.6
	CM3	**1**	54.4	46.7	41.3	10.0
		2	61.5	38.4	35.4	8.0
	CM4	**1**	31.5	20.3	19.3	4.1
		2	29.4	22.6	18.4	4.2
	MAP	**1**	67.3	51.9	39.5	15.6
		2	68.3	53.7	43.8	16.3
	Check	**1**	27.4	17.2	16.3	3.5
		2	27.5	21.5	16.0	3.9
Newdale CL	**SM1**	**1**	56.7	32.3	36.3	7.1
		2	59.4	40.1	41.2	7.9
	SM2	**1**	56.3	27.3	34.5	6.6
		2	53.9	41.0	35.8	6.2
	SM3	**1**	63.6	32.1	41.6	8.3
		2	57.2	42.4	39.3	7.8
	SM4	**1**	66.7	39.8	43.9	9.3
		2	46.6	33.1	33.8	7.1
	CM1	**1**	54.1	28.6	30.0	6.5
		2	60.3	30.3	35.4	7.8
	CM2	**1**	59.1	37.2	35.5	7.0
		2	57.6	32.6	36.3	6.9
	CM3	**1**	71.5	42.7	50.1	9.3
		2	68.5	50.7	43.7	9.2
	CM4	**1**	41.6	25.5	26.5	5.1
		2	46.0	38.8	27.5	5.3
	MAP	**1**	71.1	42.1	43.9	11.8
		2	74.4	37.6	43.0	11.4
	Check	**1**	45.5	17.7	25.7	4.9
		2	42.4	19.5	26.6	5.4