Increase in phosphorus concentration of a clay loam surface soil receiving repeated annual feedlot cattle manure applications in southern Alberta

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Chang, C., Whalen, J. K. and Hao, X. 2005. **Increase in phosphorus concentration of a clay loam surface soil receiving repeated annual feedlot cattle manure applications in southern Alberta**. Can. J. Soil Sci. **85**: 589–597. Migration of P from soils to water resources poses a risk of surface water eutrophication, and increase in P concentration in soils through manure or fertilizer addition would exacerbate this problem. Investigating the rate of increase in P concentration of surface soil receiving livestock manure is crucial to the development of best manure management strategies and prevention of eutrophication of aquatic systems. In this study, the changes in P concentrations of surface soils (0- to 15-cm depth) receiving 25 annual manure applications at rates of 0, 30, 60 and 90 Mg ha^{-1} yr^{-1} under non-irrigated conditions and at rates of 0, 60, 120 and 180 Mg ha^{-1} yr^{-1} under irrigated conditions were examined. The soil test P (STP) and total P (TP) of the surface soil increased with the TP through manure application over a 25-yr period. The STP pool was about 38% of the soil TP pool, similar to ratios of STP to TP in feedlot cattle manure. While the high proportion of STP to TP could be beneficial for crop production, it could also increase the potential for P losses from these soils through runoff and leaching. The changes in TP and STP concentrations of the surface soil were modelled with an exponential rise to maximum function:

$$TP = 0.69 + 5.06\ (1 - e^{(-0.087x)})$$

and

$$STP = 0.029 + 2.21\ (1 - e^{(-0.082x)})$$

where x is the cumulative TP applied. Although the model was developed for a specific soil and type of manure, it could be adapted to other soils or manure sources by adjusting the model coefficients for the particular soil and/or manure type. These adjustments would not require as extensive a data set as was required to develop the original model. This model could be used to determine the amount of TP that could be applied for a given critical STP. Producers, regulatory agencies, planners, and extension specialists could also use this model to make decisions on manure P management.

Key words: Long-term cattle manure application, total phosphorus, available phosphorus, rate of accumulation, non-irrigated and irrigated cropping

Chang, C., Whalen, J. K. et Hao, X. 2005. **Hausse de la concentration de phosphore dans un loam argileux superficiel enrichi annuellement de fumier de bovin dans le sud de l'Alberta**. Can. J. Soil Sci. **85**: 589–597. La migration du P du sol dans l'eau pose le risque d'une eutrophisation des eaux de surface. Une hausse de la concentration du P dans le sol consécutivement à l'utilisation de fumier ou d'engrais aggraverait le problème. Il est donc capital d'établir avec quelle rapidité la concentration de P augmente dans le sol de surface bonifié avec du fumier si l'on veut échafauder les meilleures stratégies possibles pour gérer cet amendement et éviter l'eutrophisation des systèmes aquatiques. Les auteurs ont examiné la variation de la concentration du P dans les sols de surface (profondeur de 0 à 15 cm) qui avaient reçu 25 applications annuelles de fumier à raison de 0, 30, 60 et 90 Mg par hectare et par année sans irrigation ou de 0, 60, 120 et 180 Mg par hectare et par année avec irrigation. L'application de fumier pendant 25 ans augmente la concentration de P dans l'échantillon de sol testé (PE) et la concentration totale de P (PT) dans la couche superficielle. Le réservoir de PE correspond à environ 38 % du réservoir de PT du sol, ce qui correspond au ratio entre le PE et le PT dans le fumier. Bien qu'elle puisse profiter aux productions végétales, la forte proportion de PE par rapport au PT pourrait aussi accroître les pertes de P du sol par ruissellement et lixiviation. La variation de la concentration de PT et de PE dans le sol de surface a été modélisée par élévation exponentielle à la fonction maximale :

$$PT = 0{,}69 + 5{,}06\ (1 - e^{(-0{,}087x)})$$

et

$$PE = 0{,}029 + 2{,}21(1 - e^{(-0{,}082x)})$$

Abbreviations: **STP,** soil test phosphorus; **TP,** total phosphorus

où x représente la quantité de PT cumulative venant de l'amendement. Quoique ce modèle ait été élaboré pour un sol précis et un type de fumier particulier, on pourrait l'adapter à d'autres sols et amendements en ajustant les coefficients en conséquence. Un tel ajustement n'exigerait pas autant de données que celles qu'il a fallu réunir pour mettre au point le modèle. Ce dernier pourrait servir à établir la quantité de PT qu'on pourrait appliquer, sachant le seuil critique de PE. Les agriculteurs, les organismes de réglementation, les planificateurs et les vulgarisateurs pourraient aussi s'en servir pour prendre des décisions sur la gestion du P du fumier.

Mots clés: Applications prolongées de fumier de bovin, phosphore total, phosphore disponible, taux d'accumulation, cultures irriguées et non irriguées

Phosphorus has long been recognized as the limiting nutrient in most freshwater ecosystems. Enrichment of P in surface water is often the major cause of eutrophication (Schindler 1977; Correl 1998). The agricultural sector is implicated as a leading source of fresh water contamination in the United States (Environmental Protection Agency, 1995), Britain (Burt et al. 1996; Moss et al. 1996), the Netherlands (Steenvoorden and Oosterom 1979), and Northern Ireland (Foy et al. 1995).

Phosphorus is an essential element for plant growth; therefore, it is commonly added to soil in the form of mineral or organic fertilizer to increase crop yield. However, P application in excess of crop requirements often results in increased total P (TP) and soil test P (STP) concentrations in surface soil. Traditionally, animal manure application rates have been developed to meet crop N requirements. This often causes accumulation of P in soils because there is a higher proportion of P to N in the manure than is required by crops (Leaver 1984; Nguyen and Goh 1992; Greatz and Nair 1995). Therefore, in intensive livestock production areas, soils are often found to be enriched with P due to manure application or disposal (Chang et al. 1991; Whalen and Chang 2001; Withers et al. 2001). The STP concentration in intensive livestock production areas can be as high as two or three times the concentration required for optimum plant growth (Sharpley et al. 1998). Greatz and Nair (1995) showed that the TP concentration of a Spodosols in Florida varied from 1680 kg ha^{-1} in areas with high cattle density to 34 kg ha^{-1} in areas with low cattle density. Whalen and Chang (2001) showed that after 16 annual applications of feedlot cattle manure, although some of the applied P was taken by the crop, a considerable amount accumulated in the top 150 cm of the soil under nonirrigated conditions in southern Alberta, Canada. However, Whalen and Chang (2001) found that 1.4 Mg P ha^{-1} was not recovered in crops and soils in irrigated plots when manure was applied at a rate of 180 Mg ha^{-1} yr^{-1}. An increase in STP often leads to a significant increase in the amount of water-soluble P in soils (Pautler and Sims 2000; Griffin et al. 2003) and an increase in dissolved P in runoff water (Pote et al. 1996; Andraski and Bundy 2003; Fang et al. 2002; Schroeder et al. 2004; Sims et al. 1998). Therefore, there are growing concerns over P accumulation in agricultural soils receiving animal manure.

Various guidelines have been proposed to manage the use of livestock manure on agricultural land. Increasingly, limits are based on the soil P status. However, soil types, landforms, and management practices that can potentially influence P transport and hence water quality are also considered, and these have been included in the P index system proposed by Lemunyon and Gilbert (1993). A key component of the P index is STP value, which is routinely determined for agronomic purposes. The STP is related to the potential for P transfer from soil to water (Heckrath et al. 1995; Pote et al. 1996), and there is growing interest in using critical levels of STP to assist development of manure and fertilizer management guidelines and to protect water quality from non-point source pollution. In the eastern and southern United States, critical levels of STP in surface soils has been suggested to range from 0.075 g P kg^{-1} to 0.2 g P kg^{-1} with various extraction methods (Sharpley et al. 1996; Sharpley and Tunney 1999; Gartley and Sims 1994).

Whalen and Chang (2001) have presented results for the first 16 yr of this study, which included the P balance, crop uptake and P loss from the 0–150 cm soil depth. This study presents results on the effects of cumulative livestock manure application on the surface soil P concentration dynamics. The objective of this paper was to determine the rate of increase in TP and STP concentration of surface soil in response to 25 annual applications of feedlot cattle manure under both non-irrigated and irrigated conditions. In addition, the relationship between manure P applications and STP concentrations in surface soil (0 to 15 cm) was used to estimate how much manure could be applied before a critical STP level would be reached.

MATERIALS AND METHODS

The research site is located at the Agriculture and Agri-Food Canada Research Centre in Lethbridge, Alberta, Canada. In 1973, an experiment was initiated to determine the effects of repeated annual application of cattle feedlot manure on the productivity of non-irrigated and irrigated soils. The soil is a calcareous Orthic Dark Brown Chernozemic clay loam (Haplic Kastanozen in FAO Soil Classification System). Some of the initial soil physical and chemical properties are shown in Table 1. The plot area was cropped annually with barley (*Hordeum vulgare* L.) from 1974 to 1995, canola (*Brassica rapa* L.) in 1996 and corn (*Zea mays* L.) on irrigated soils and triticale (*Triticosecale* L.) on non-irrigated soils in 1997 and 1998. All aboveground biomass was removed during harvest except for about 10 cm of stubble. The barley straw was bailed and both corn and canola residues were physically removed from the plot areas. Details of the research site and the effect of long-term manure amendments on soil chemistry, fertility, P accumulation and balance, and physical properties have been report-

Table 1. Initial soil characteristics

Depth (cm)	Sand (%)	Clay (%)	pH	Organic C (%)	Total N (%)	Total P (g kg^{-1})	Bulk density (Mg m^{-3})
0–15	38.6	39.4	7.7	1.46	0.26	0.69	1.22
15–30	38.7	40.0	7.8	1.10	0.22	0.69	1.41
30–60	47.8	29.7	7.9	0.57	0.13	0.58	1.41
60–90	39.9	34.3	7.9	0.33	0.10	0.58	1.54
90–120	45.8	29.3	7.9	0.23	0.08	0.59	1.63
120–150	47.3	30.0	7.8	0.19	0.08	0.59	1.67

ed previously (Sommerfeldt and Chang 1985; Chang et al. 1991, 1993; Chang and Janzen 1996; Whalen and Chang 2001; Hao et al. 2003, 2004).

Experimental Design

Solid feedlot cattle manure was applied annually each fall after harvest starting in 1973. The manure was incorporated immediately after application by one of three methods: plow, rototiller or cultivator plus disk. Within each tillage treatment (main plot), manure was applied to subplots (7.5 by 15 m) at the following rates: 0, 30, 60 and 90 Mg ha^{-1} yr^{-1} (wet weight) to a non-irrigated soil and 0, 60, 120 and 180 Mg ha^{-1} yr^{-1} (wet weight) to an irrigated soil. Main and subplot treatments were assigned randomly and replicated three times.

Recommended manure applications in this area were 30 Mg manure ha^{-1} yr^{-1} (wet weight) for non-irrigated soils and 60 Mg ha^{-1} yr^{-1} (wet weight) for irrigated soils at the initiation of the experiment (Alberta Agriculture 1980). However, in intensive livestock production areas such as Lethbridge County, Alberta, the actual rates of manure application often exceed those recommended rates due to limited cropland available for manure application. Thus, the land application of manure was used as a desposal of feedlot cattle manure rather than nutrient recycling. Therefore, higher than recommended manure application rates were selected for this study in order to evaluate the sustainability of these practices. Soil properties and crop production were not significantly affected by tillage (Sommerfeldt et al. 1988; Chang et al. 1990) and starting in 1986, manure was incorporated in all subplots with a cultivator to a depth of 10 to 15 cm. This increased the number of replicates to nine for each manure treatment.

The manure came from an open, unpaved commercial cattle feedlot. It did not contain bedding, and was stored for 1 to 2 yr before application. The feedlot cattle manure was analyzed each year over the 25-yr period and on average on a dry weight basis it contained 17.5 ± 7.5 g C kg^{-1} total C, 15.9 ± 0.7 g N kg^{-1} total N and 6.1 ± 0.1 g P kg^{-1} total P. The Olsen extractable P concentration in manure varied considerably from year to year (13 to 62% of TP), with an average value of 2.3 g P kg^{-1}. The average water content of the manure was 720 g water kg^{-1} dry manure.

Soil and Manure Analysis

Eight cattle feedlot manure samples were taken every year for chemical analysis when manure was applied. Soil samples were collected annually, except in 1989, 1991–1993 and 1996–1997. After harvest and prior to manure application, two soil cores were extracted from each plot. Soil cores were subdivided into six increments (0 to 15-cm, 15 to 30-cm, 30 to 60-cm, 60 to 90-cm, 90 to 120-cm, and 120 to 150-cm), air-dried, and ground (<2 mm). The extractable P concentration in soil (STP) and manure samples was measured as $NaHCO_3$-soluble phosphorus (Olsen et al. 1954) and TP was measured by Na_2CO_3-fusion (Jackson 1958). Only the data from the surface 15 cm soil were reported. The surface soil (0- to 15-cm depth) was a clay loam with 39.4 clay and 38.6% sand, and its STP and TP concentrations were 0.014 g P kg^{-1} soil and 0.68 g P kg^{-1}, respectively, at the study area in 1973 prior to any feedlot cattle manure application.

Calculations for Cumulative Phosphorus Application and Phosphorus Accumulation in Soils

The quantities of TP and STP applied annually through cattle feedlot manure were calculated based on the amount of manure dry weight per area and TP or STP concentration in the manure each year. The cumulative manure TP (or STP) applied was the sum of TP (or STP) applied over the years during the study period.

P Accumulation Model and Statistical Analysis

The TP and STP concentrations in feedlot cattle manure are usually much higher than that of soil. If feedlot cattle manure with a relatively constant P concentration is applied to soil and P loss from soil is small, the soil TP and STP concentrations following manure application will increase with the amount of manure P applied. Under this scenario, (1) the rate of increase in soil TP and STP concentration would decrease with cumulative amount of TP applied and (2) the concentrations (TP and STP) will eventually reach a maximum. The models such as second order polynomial function and power function could not meet both above-mentioned criteria. Therefore, an "Exponential Rise to Maximum" function $y = a + b\ (1 - e^{(-cx)})$ was selected to model soil TP and STP concentration changes in response to manure P application. Where y is soil TP or STP concentration, x is the cumulative manure TP applied, and a (g kg^{-1}), b (g kg^{-1}) and c are constants. The constant a is the initial soil TP or STP concentration, $(a + b)$ is the maximum for TP or STP concentration of the soil and c is the constant describing the rate at which the soil TP or STP reach the maximum concentration. The constants, a, b, and c were obtained through regression analysis by relating the soil TP or STP concentrations (0- to 15-cm) to cumulative manure TP applied with the prescribed model using the PROC REG and PROC NONLIN functions of SAS (SAS Institute, Inc. 1999). No constraint on maximum for the model was imposed during the regression analysis. Analysis of covariance of the equation, demonstrated that the coefficients of regression equations did not differ significantly between non-irrigated and irrigated blocks (Milliken and Johnson 2002); therefore, all the data points were pooled for the regression analysis.

The model relating STP concentration in soil to the cumulative manure TP applied was used to estimate the amount of manure TP that could be applied from cattle feedlot manure to achieve a critical STP concentration (0- to 15-cm depth).

RESULTS

Phosphorus in Cattle Feedlot Manure

The cumulative manure TP applied between 1973 and 1998 was 2.5, 5.0, and 7.4 Mg P ha^{-1} in non-irrigated plots amended with 30, 60 and 90 Mg ha^{-1} yr^{-1}, respectively. During the same period, irrigated plots amended with 60, 120 and 180 Mg ha^{-1} yr^{-1} had cumulative manure TP input of 5.0, 9.4 and 14.1 Mg P ha^{-1}. Linear regression analysis of cumulative manure TP and cumulative manure extractable P indicates that 38% of manure TP was extractable using the Olson-P method (Fig. 1), which is consistent with the range of 17 to 53% extractable P in animal manure reported by others (Greatz and Nair 1995; Eghball and Power 1999).

Rate of Soil TP Concentration Changes

The relationship between the soil TP concentration (0- to 15-cm depth) and the manure TP concentration followed the "Exponential Rise to Maximum" model with 95% of the variation in soil TP concentration explained by the model (Fig. 2). The maximum soil TP concentration projected by the regression model was 5.7 g P kg^{-1} soil, which was less than the average manure TP concentration of 6.1 g P kg^{-1}. In 25 yr, 14.1 Mg P ha^{-1} was applied to the soil and the soil TP concentration had reached 4.3 g P kg^{-1}, or about 75% of the projected maximum concentration (5.7 g P kg^{-1}).

The intercept of the equation a estimates the soil TP concentration before any manure P was applied to be 0.689 g P kg^{-1}, which is close to 0.682 g P kg^{-1} measured at the study site before manure applications began in 1973. The rate of increase in soil TP concentration of manured soil decreased as the cumulative amount of applied TP increased, from 0.44 g P kg^{-1} for each Mg P ha^{-1} at the start of the experiment to 0.13 g P kg^{-1} for each Mg P applied after 14.1 Mg P ha^{-1} was applied (Fig. 2). The rate of increase in soil TP concentration is expected to approach zero as the soil TP concentration reaches the maximum value of 5.7 g P kg^{-1}.

Rate of Increase in STP Concentration

The STP concentration of the manured surface soil (0- to 15-cm depth) increased with cumulative manure TP applied, following the "Exponential Rise to Maximum" model (Fig. 3). Based on the model, the rate of increase in STP concentration could be calculated as follows: $\frac{dy}{dx} = bce^{-cx}$. The rate of increase of STP was initially 0.18 g P kg^{-1} and it decreased to 0.06 g P kg^{-1} after 25 yr. After 14.1 Mg P ha^{-1} had been applied, the STP concentration of the surface was 1.54 g kg^{-1}, which was about 69% of the maximum value ($a + b$) of 2.23 g P kg^{-1}. The intercept a estimates the STP concentration of the surface soil before any manure was applied to be 0.029 g P kg^{-1}, higher than the 0.014 g P kg^{-1} measured in the soil in 1973.

The maximum STP concentration projected by the regression model was 2.23 g P kg^{-1} soil, which was about 39% of the projected maximum TP.

STP/TP Ratio in Soil

The STP concentration of surface soil increased linearly with the TP concentration (Fig. 4), suggesting that for every 1 g kg^{-1} increase in soil TP concentration, STP increased by 0.39 g kg^{-1}. In other words, 39% of the TP was in the form of STP, similar to the values of the cattle manure applied (Fig. 1). However, the STP/TP ratio in soil was much lower when the STP or TP concentration is low (Fig. 5), reflecting the initial soil STP/TP ratio of <0.026. As more cattle manure was applied, the STP/TP ratio also increased and reached the maximum value of 0.38, the values observed in the cattle manure (Fig. 5).

DISCUSSION

The results of this study showed that both soil TP and STP concentrations increased with the amount of manure applied regardless of the annual application rates. The rates of soil TP and STP increase are not linear but followed "Exponential Rise to Maximum" models (Figs. 2 and 3). The rates of increase were greater during earlier period of manure application. Although TP and STP concentration of surface in this 25-yr study with high annual rates of manure applications have not reached the maximum values as projected by the models, the models show that those maximum values would not be reached for many decades at the very least. However, from the model with an estimated cumulative application of 50 Mg P ha^{-1}, TP concentration of soil would approach 5.7 g P kg^{-1}, which approaches the average TP concentration of 6.1 g P kg^{-1} of the manure applied. In other words, if the assumptions associated with the model hold beyond 25 yr or cumulative application rates of up to 14.1Mg P ha^{-1}, it would require the application of 8196 Mg ha^{-1} of dried feedlot cattle manure for at least 79 yr of annual manure applications at the rate of 180 Mg wet weight ha^{-1} yr^{-1} (42% water content by weight) or 474 yr of annual applications at the rate of 30 Mg wet weight ha^{-1} yr^{-1}) to approach the maximum STP and TP levels in the soil. Although these are projected values, they illustrate the difficultly of projecting the long-term effects of animal manure on soil and the environment with results from 25-yr studies let alone short-term studies that are run for 5 yr or less.

For STP, the model projects the maximum concentration to be 2.23 g P kg^{-1} (Fig. 3), which is a similar to the 25-yr average STP (Olson-extractable P) of 2.3 g P kg^{-1} in the manure used in this study. The similar values between projected maximum for both TP and STP and those of applied

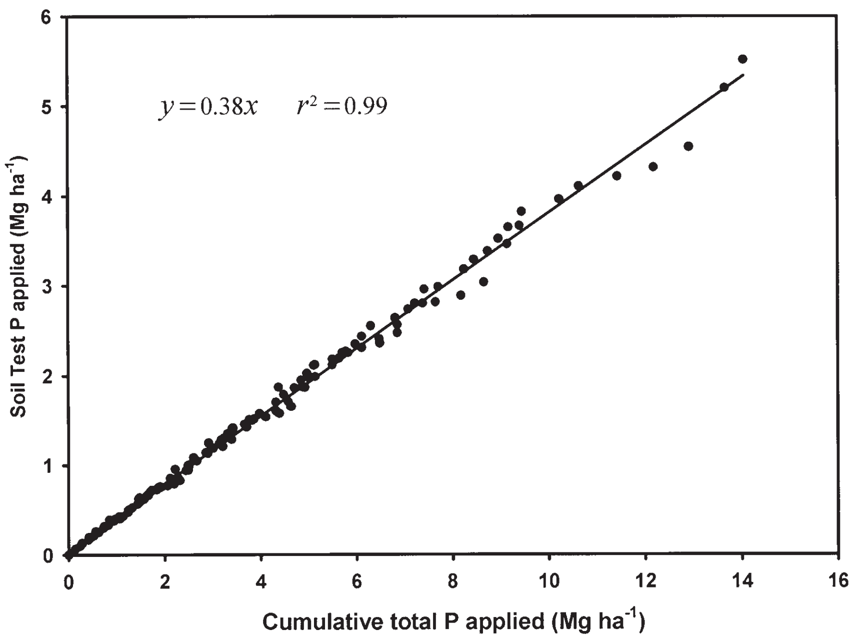

Fig. 1. Relationship between TP and STP in cattle feedlot manure applied over 25 yr.

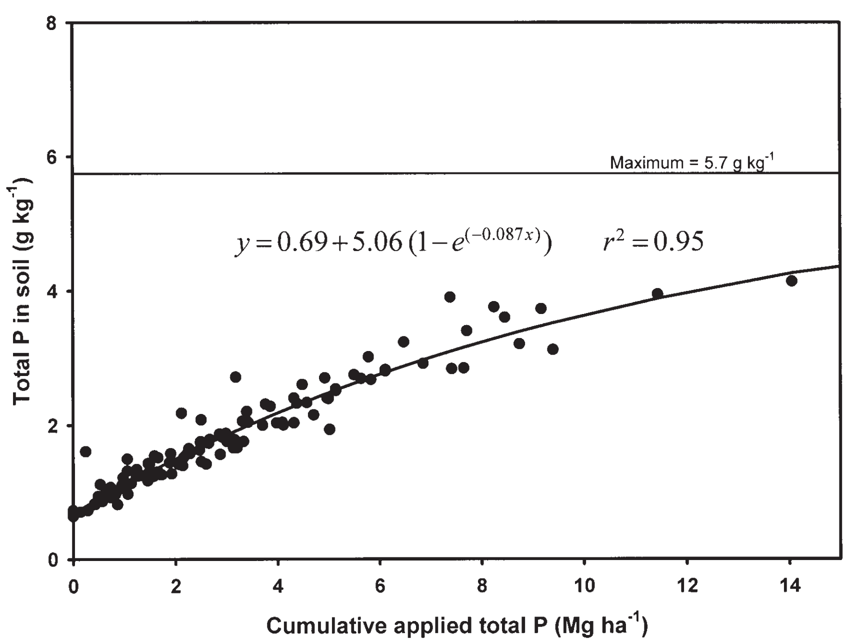

Fig. 2. Relationship between soil TP concentration (0- to 15-cm depth) and the cumulative amount of manureTP applied over 25 yr.

manure without constrains imposed on the model were expected. The P concentration processes such as the loss of organic matter through decomposition and dilution processes such as P leaching and crop uptake might play minor roles, or both processes were in balance in this study. The P balance of this study has been reported by Whalen and Chang (2001).

As indicated previously, the critical STP level in surface soils for the eastern and southern United States ranges from 0.075 g P kg^{-1} to 0.2 g P kg^{-1} (Gartley and Sims 1994; Sharpley et al. 1996; Sharpley and Tunney 1999). When the STP level exceeds these critical limits, the amount of P applied through mineral fertilizer or livestock manure can only be at the rate of crop P uptake in that crop year. If we consider 0.2 g P kg^{-1} to be a critical STP level, based on the model in Fig. 3, 0.98 Mg P ha^{-1} manure TP must be applied to reach this critical STP level [manure contains 6.1 g TP kg^{-1} manure dry weight and a 42% moisture content (wet weight basis)].

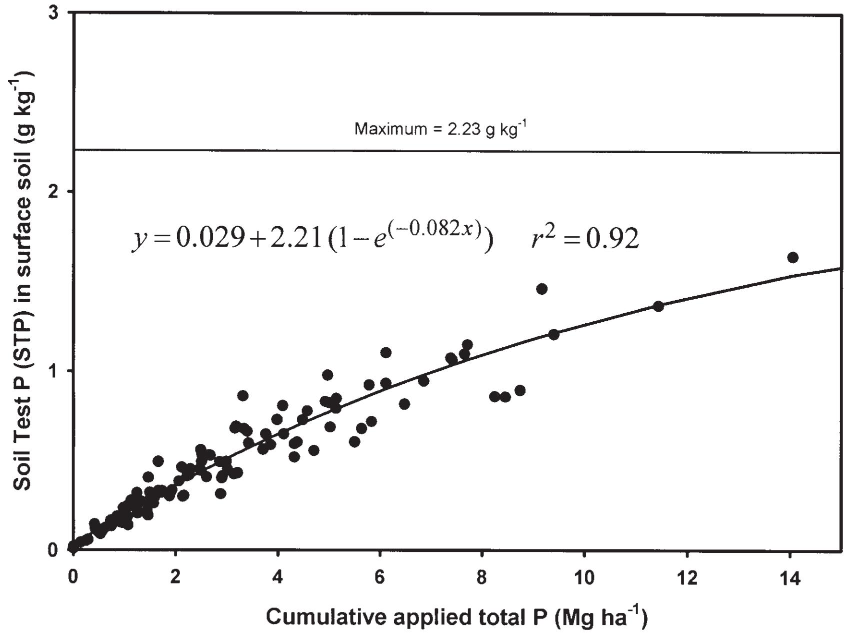

Fig. 3. Relationship between STP concentration (0- to 15-cm depth) and the cumulative amount of manureTP applied over 25 yr.

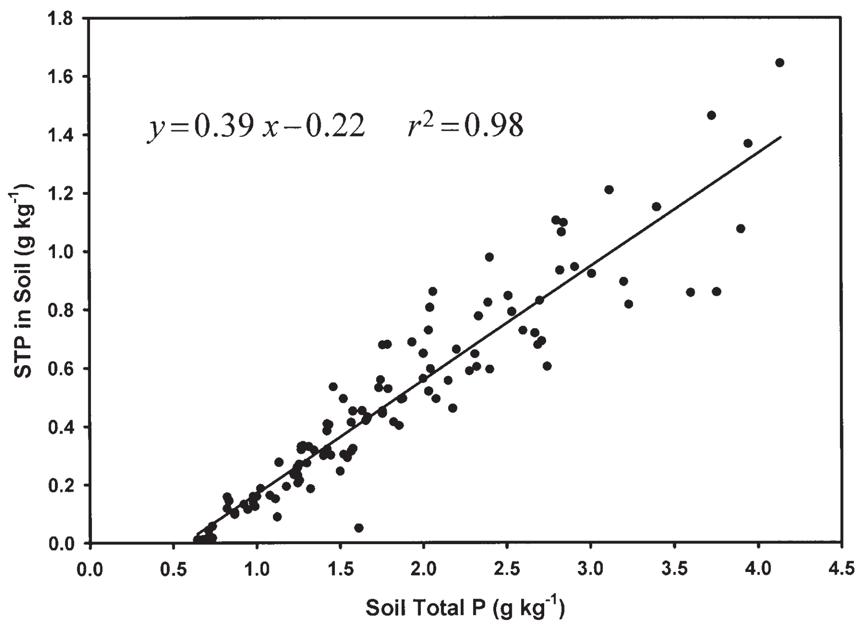

Fig. 4. Relationship between STP and TP concentrations in surface soils (0- to 15-cm depth) receiving repeated cattle feedlot manure applications under non-irrigated and irrigated conditions over 25 yr.

Based on these values, the STP concentration in the 0- to 15-cm depth could reach the critical STP level of 0.2 g P kg^{-1} after 10 annual manure applications of 30 Mg (wet weight) ha^{-1} yr^{-1} or less than two annual manure applications at a rate of 180 Mg (wet weight) ha^{-1} yr^{-1} according to the model. The measured results showed that STP concentrations were 0.24 g P kg^{-1} after 10 annual applications at 30 Mg ha^{-1} yr^{-1} and 0.4 g P kg^{-1} after two annual applications at 180 Mg ha^{-1} yr^{-1}. If cattle feedlot manure was applied at 14 Mg (wet weight) ha^{-1} yr^{-1}, a rate identified to provide sufficient nitrogen for irrigated barley silage production while minimizing N leaching losses in the semi-arid southern Alberta climate (Chang and Entz 1996), it would take 20 yr for surface soil to reach the critical STP level.

The critical STP level of 0.2 g P kg^{-1} is the upper limit reported in the scientific literature. Should a more conserv-

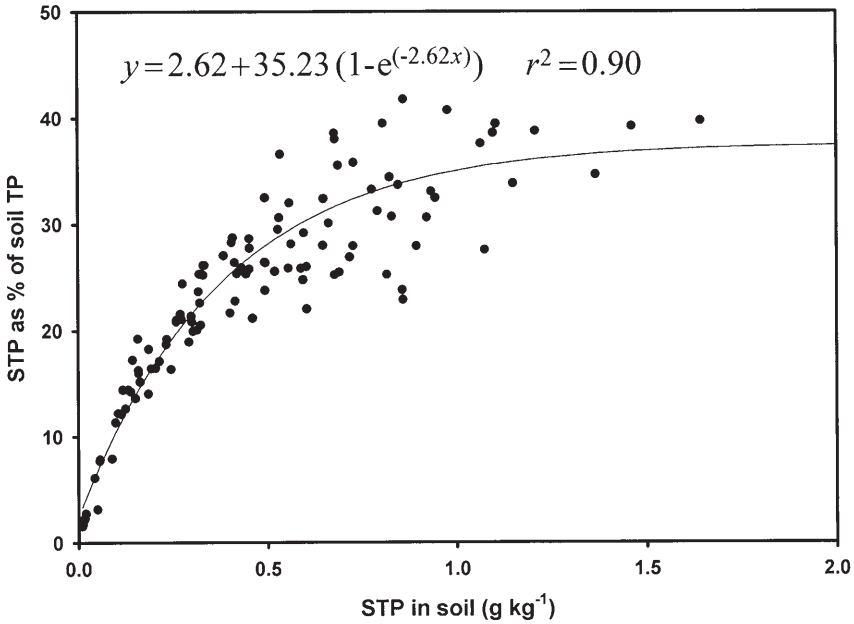

Fig. 5. Relationship between the STP/TP ratio and STP concentration in surface soils (0- to 15-cm depth) receiving repeated cattle feedlot manure applications under non-irrigated and irrigated conditions over 25 yr).

ative critical STP level be adopted, considerably less manure could be applied to soils. When the STP concentration reaches the critical STP level, it is expected that fertilizer P applications should equal the crop P requirements. In this situation, for this study the maximum manure application would be 5.2 and 8.8 Mg (wet weight) ha^{-1} yr^{-1} for non-irrigated and irrigated treatments, respectively, based on the average manure TP concentration, moisture content and barley P uptake found from this study. The annual amount of cattle manure removed from a confined feeding operation is, on average, 2.2 Mg head^{-1} yr^{-1} (Alberta Agriculture, Food and Rural Development 2000) and the average P concentration of manure in this area is similar to that of the manure used for this study. Therefore, in order for a confined feeding operation to be sustainable after a critical STP level is reached (regardless of the concentration value), a land area of 0.42 and 0.25 ha yr^{-1} for each head of cattle is required for non-irrigated and irrigated land, respectively, and these areas are three to four times more than the current guidelines (0.125 and 0.062 ha per head) in Alberta (Alberta Agriculture, Food and Rural Development 2000).

The assumptions of the models in Figs. 2 and 3 are that cumulative manure TP applied has to be in excess of crop uptake and other losses. Whalen and Chang (2001) showed that the average amounts of crop TP uptake by barley were 12 and 31 kg P ha^{-1} yr^{-1} for non-irrigated and irrigated treatments, respectively, a relatively small amount compared with the annual manure TP application of at least 100 kg P ha^{-1} yr^{-1} and 201 kg P ha^{-1} yr^{-1} for the non-irrigated and irrigated blocks, respectively, in this study.

The STP/TP ratio in soil increased from 0.026 to 0.37, close to the predicted maximum of 0.38 (Fig. 5) and manure STP/TP ratio. The results suggested that with the amount of P applied, the STP/TP ratio of the soil would be dominated by manure P. The STP fraction is not only readily available for crop uptake, but it is also most likely to be transported through leaching and runoff. Therefore, the potential for P pollution in waterways due to P transport from agricultural soils will increase as the STP concentration increases.

Implications for Manure P Management

The model describes how TP or STP concentration of surface soil responds to the amount of TP applied [$y = a + b\,(1 - e^{(-cx)})$] and suggests TP or STP concentration in the surface soil (y) is a function of initial soil TP or STP concentration (a), and P concentration in manure applied (x). Further, both soil initial P (a) and manure STP and TP concentration and application rates contribute to the maximum TP or STP ($a + b$) of the soil. Parameter (c), which controls the rate of P increase, is a function of soil and manure properties. In addition, the rate of increase in soil TP and STP concentration is given by $\frac{dy}{dx} = bce^{-cx}$, and so it depends on the constants b and c, as well as on the amount or rate of manure P application x, since x is a function of P concentration in the manure if the TP or STP concentration of manure could be reduced it would not only reduce x and b to slow down the rate of increase in soil TP or STP concentration, but it would also reduce the maximum value of soil TP and STP concentrations which could be reached by repeated applications of manure. If the maximum TP and STP could be reduced to less than a selected critical level, there would be no limit on how much manure P could be applied, because soil STP concentration would never reach a level to cause environmental concerns. The strong correlation between TP and STP in the soil or manure suggests that reduction in TP could also slow down the rate of increases and maximum values of STP in surface soil. Reducing the STP/TP ratio in manure could be an alternative solution to reduce STP accumulation. Manure composting usually increases TP and STP concentration and the STP/TP ratio. Therefore, composting would not be the best management solution for manure P. Lowering the P level in manure by adding an amendment with low P material such as wood chips, straw or other organic materials would not be the best solution either because the total amount of material to be handled would increase and make manure application less economical. The TP or STP/TP ratio reduction in manure through either feed additives or by using technologies that recover P from the manure would be better alternatives than composting or mixing the manure with other organic amendments.

The "Exponential Rise to Maximum" models describing relationships between TP or STP concentration in surface soil and the amount of TP applied developed by this study should be applicable to and easily adapted to other soils and types of manure. Since the relationship between cumulative TP applied and TP or STP of soil is known, the coefficients of the model could be defined with fewer experimental data. The model will be extremely useful to policy makers, producers, and extension specialists as they develop better strategies for manure P management.

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