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ARTICLE

Phosphorus accumulation in Canadian agricultural soils over 30 yr

Keith Reid and Kimberley D. Schneider

Abstract: Phosphorus (P) loss to freshwater is a key driver of eutrophication, and understanding the scale and spatial distribution of potential P sources is a key pre-requisite for implementing policies for P management to minimize environmental impacts. Soil test P (STP) is a useful indicator of the accumulation of P in soils, but these data are not readily available for most agricultural land in Canada, so the cumulative P balance (P inputs as manure or fertilizer minus removal of P in crops) is calculated as a proxy for this value. Cumulative P balance is an important calculation within the indicator of risk of water contamination by P, so allocations of manure and fertilizer P to cropland were updated within the calculation of P balance, and for Ontario, data from 1961 to 1980 were added to account for P applications during that period. The STP concentrations were calculated from the resulting cumulative P balances. When compared with reported STP concentrations, the predicted concentrations showed a statistically significant regression at the national ($R^2 = 78\%$) and provincial scale (Ontario, $R^2 = 36\%$; Prince Edward Island, $R^2 = 36\%$; Manitoba, $R^2 = 72\%$; British Columbia, $R^2 = 40\%$). There was significant variation in the cumulative P balance across Canada, with the highest values corresponding with areas of high livestock density, whereas large zones of P deficit were detected across the Prairies.

Key words: phosphorus, water quality, farming systems, nutrient balances.

Résumé : La contamination de l'eau douce par lixiviation du phosphore (P) est une des principales raisons de l'eutrophisation. Avant d'instaurer des politiques pour mieux gérer cet élément et en minimiser les répercussions environnementales, on doit absolument déterminer l'ampleur du phénomène et établir la répartition des sources de P dans l'espace. Le dosage du P par analyse du sol donne une bonne idée du P qui s'est accumulé dans le sol, mais ces données sont difficiles à obtenir pour la majeure partie des terres cultivées au Canada. C'est pourquoi on utilise le bilan cumulatif du P (quantité de P dans les intrants comme le fumier ou les engrais moins celle retirée par les plantes) comme valeur de remplacement approximative. Le bilan cumulatif du P est un facteur important dans l'évaluation des risques de contamination de l'eau par cet élément. Pour cette raison, on a actualisé la part que le P représente dans le fumier et les engrais épandus sur les terres dans le calcul du bilan. Les données de 1961–1980 ont été ajoutées à celles de l'Ontario afin de prendre en compte la quantité de P appliquée durant cette période. La concentration de P dans le sol a ensuite été établie à partir du bilan cumulatif résultant. Quand on la compare aux résultats de l'analyse du sol, on constate que la concentration prévue illustre une régression significative à l'échelle nationale ($R^2 = 78$ %) et provinciale (Ontario, $R^2 = 36$ %; Île-du-Prince-Édouard, $R^2 = 36$ %; Manitoba, $R^2 = 72$ %; Colombie-Britannique, $R^2 = 40$ %). Le bilan cumulatif du P varie sensiblement au Canada, les valeurs les plus élevées correspondant aux endroits où on pratique l'élevage intensif du bétail, alors qu'il existe de vastes zones carencées en P dans les Prairies. [Traduit par la Rédaction]

Mots-clés : phosphore, qualité de l'eau, systèmes agricoles, bilan des éléments nutritifs.

Introduction

Phosphorus (P) loss to surface freshwater is a key driver of environmental degradation (Jarvie et al. 2013; Scavia et al. 2014), including blooms of both harmful (e.g., *Microcystis*) (Conroy et al. 2014; Steffen et al. 2014; Simic et al. 2017) and nuisance (e.g., *Cladophora*) algae (Howell and Dove 2017), along with contributing to the development of hypoxic zones that impact fish habitat (Bouffard et al. 2013; Scavia et al. 2014). Although agricultural runoff is not the only source of P loading to surface

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Table 1. Soil test methods, starting dates, and initial concentrations for Canadian provinces.

Provinces	STP method	Starting date	Initial assumed STP concentration (mg P kg^{-1})	Δ STP/Δ Cumulative P balance (mg P kg^{-1}/kg P ha^{-1})
Atlantic Canada, Quebec	Mehlich 3	1976	5	0.1124
Ontario	Olsen	1961	3	0.0701
Manitoba	Olsen	1976	3	0.0701
Saskatchewan, Alberta, British Columbia	Modified Kelowna	1976	4	0.0847
National (IPNI comparison)	Bray P1	Same as province	5	0.0906

Note: P, phosphorus; STP, soil test phosphorus; IPNI, International Plant Nutrition Institute.

water, it is significant in many areas and is implicated as the dominant source to some of the most heavily impacted waters (Sharpley et al. 2003; Michaud et al. 2004; Joosse and Baker 2011; Bunting et al. 2016).

The loss of P from non-point agricultural sources is a result of an interaction between source and transport factors (Sharpley et al. 2012). One of the key source parameters for P loss from agricultural runoff is the accumulation of P in the soil, as measured with an agronomic soil test (Sharpley et al. 2002; Vadas et al. 2005; Wang et al. 2015). This directly influences the concentration of dissolved P in runoff (Wang et al. 2010), the concentration of bio-available particulate P (Sharpley 1985), and indirectly, the accumulation of P in plant biomass that could be released over-winter from frozen plant tissue (Sharpley and Smith 1989; Roberson et al. 2007; Maltais-Landry and Frossard 2015). Soil test P data for individual fields are not available at a national scale, so for indicator of risk of water contamination by P (IROWC-P), these concentrations have been estimated by correlating with the cumulative P balance (van Bochove et al. 2012). The original calculations by van Bochove et al. (2012), however, assumed that manure P displaced mineral fertilizer P from land application, which generated zero fertilizer P applications for some areas despite the presence of many non-livestock farms. In addition, there was strong evidence for Ontario (but not for the other provinces) that there had been considerable P accumulation prior to 1976 (Bruulsema et al. 2011), so the assumption of a zero P balance and low STP concentration at the starting date for the model in 1976 was not valid. The calculation of P balance was updated to correct these deficiencies.

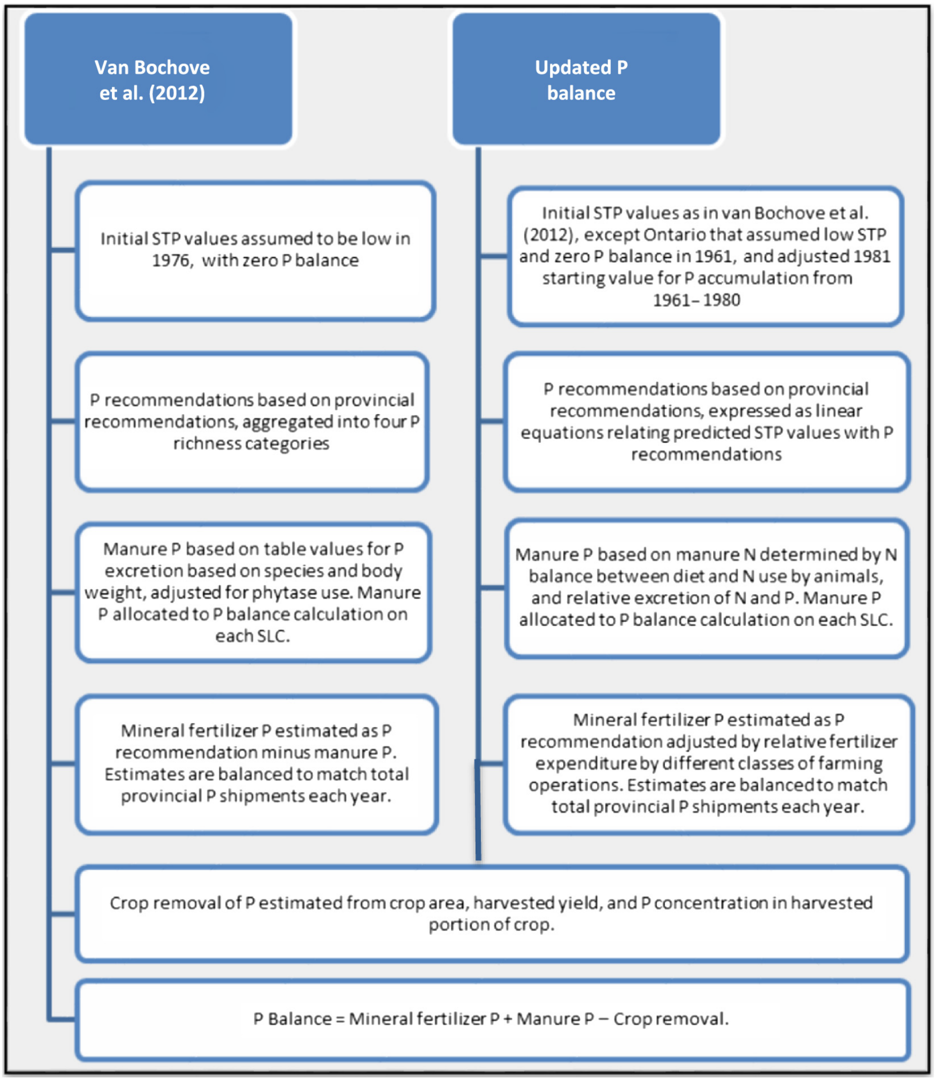
The objectives of this paper are to describe the updated techniques used to predict the source component for assessing the risk of soluble P loss (P_source) desorbed from agricultural soils to surface and subsurface runoff, to validate these predictions against measured soil test concentrations at the provincial and subprovincial scale, and to discuss the changes in predicted P accumulation at the Soil Landscape of Canada (SLC) polygon scale from 1981 to 2006 (Soil Landscapes of Canada Working Group 2010). The paper also identifies critical regional areas across the country on the SLC scale where the accumulation of P and, therefore, the risk of P desorption is high and where further investigation is required to protect surface water quality from P contamination by agriculture. This paper presents the results of an updated methodology for calculating the cumulative P balance since the paper by van Bochove et al. (2012) and extends the analysis for an additional 5 yr to 2011. This paper does not discuss the entire IROWC-P model, which includes risks of P loss from soil erosion, overwintering vegetation, and incidental losses from manure, and mineral fertilizer application but rather focuses on the prediction of P buildup in the soil.

Materials and Methods

The outline of the methods used to calculate the cumulative P balance for use in IROWC-P are well described in van Bochove et al. (2010*a*) and van Bochove et al. (2012). To summarize these methods, base data for crop areas, yields, and livestock numbers were acquired from Statistics Canada and interpolated to SLC polygons [Interpolated Census of Agriculture by Soil Landscapes of Canada (ICOA) 2013]. The cumulative P balance was calculated at the SLC scale as the sum of estimated manure and mineral fertilizer P applications minus the P removed in the harvested portion of the crop, accumulated over the time period from 1976 to 2011. This cumulative P balance was then multiplied by a factor (specific to each of the standard agronomic soil tests used in each province) to estimate the expected change in STP from an assumed initially low starting concentration (Table 1). However, close inspection of the results revealed that the method used did not fully account for the accumulation of P in Ontario during the 1960s and 1970s, and it over-estimated the impact of manure application on fertilizer P rates. The most obvious impact of this was that the predicted STP concentrations for Ontario were significantly lower than the median STP concentrations reported from samples analyzed in Ontario soil test laboratories (van Bochove et al. 2012).

To address these inaccuracies, new algorithms were developed to improve the allocation of mineral fertilizer and manure to SLC polygons, and provincial estimates of crop areas, yields, and livestock numbers were used to calculate P balances for the time period from 1961 to 1980 for the province of Ontario. In addition, equations used to convert P balance to STP were updated. The

Fig. 1. Comparison of P balance calculations made for the national indicator of risk of water contamination by phosphorus by van Bochove et al. (2012) with the updates presented here. STP, soil test phosphorus; SLC, Soil Landscape of Canada.



differences in approaches to calculating the P balance are shown in Fig. 1.

Manure P allocation

Manure allocation to the landscape was aligned with the predictions in the CANB model version 4.0 (Yang et al. 2011), which is used to allocate manure N to SLC polygons in the indicator of risk of water contamination by N (IROWC-N) (Drury et al. 2016). Manure generation was estimated from the numbers of each livestock species determined in the Census of Agriculture and allocated to SLC polygons (ICOA 2013). The CANB model allocates manure to crops within the SLC polygon up to an amount that provides 75% of the crop N requirements, assuming that manure is primarily used to provide N rather than P. The exception is in the province of Quebec after 2010, where there is a regulatory requirement that manure P applications not exceed crop removal. Manure P allocation adjusted to ensure this limit is not exceeded.

The manure N allocation is used to estimate the P applications to each SLC, using the ratio between the excretion of N and P by each livestock species (see Table 2). These ratios have been found to be quite consistent over a time period spanning, the adoption of phytase enzymes in feed [American Society of Agricultural and Biological Engineers (ASABE) 2005; Poulsen et al. 2006], so it was assumed that the reduction in P excretion in response to the use of phytase in livestock rations is mirrored by improvements in N use efficiency, and so it does not need to be accounted for separately.

Mineral fertilizer P allocation

Previous versions of IROWC-P assumed that mineral fertilizer P was displaced by manure P, but this is not consistent with the findings of the Farm Environmental Management Survey (Statistics Canada 2001–2006) or the recent Fertilizer Use Survey led by Pulse Canada (Canadian Field Print Initiative 2017). The allocation of

Table 2. Nitrogen:phosphorus (N:P) excretion ratio for different types of livestock.

Animal type and production grouping	N:P excretion ratio (kg N excreted kg^{-1} P)
Beef — Finishing cattle	7.5
Beef — Cow (confinement)	4.3
Beef — Growing calf (confinement)	5.3
Dairy — Lactating cow	6.4
Dairy — Dry cow	6.4
Dairy — Heifer (970 lb)	6.4
Swine — Nursery pig (27.5 lb)	6.1
Swine — Grow-finish (154 lb)	5.9
Swine — Gestating sow (440 lb)	3.5
Swine — Lactating sow (423 lb)	3.5
Swine — Boar (440 lb)	3.5
Horse — Sedentary (1100 lb)	6.8
Horse — Intense exercise (1100 lb)	6.8
Layer	3.2
Poultry — Broiler	3.4
Poultry — Turkey (males)	3.3
Poultry — Turkey (females)	3.6
Poultry — Duck	3.0

mineral fertilizer was recalculated to account for the relative fertilizer expenditures by different types of farming operations, as a better indicator of the rates of P fertilization. This approach utilizes the following assumptions.

- Regionally, P mineral fertilizer use is proportional to the P requirements of crops grown within each SLC polygon.
- P fertilizer expenditures represent a constant proportion of total expenditures on fertilizer and lime across classes of farming operations.
- Allocation of P fertilizer to location of farm headquarters does not skew distribution significantly.
- As a group, farmers allocate a greater part of their fertilizer expenditures to the fields, where they will give the greatest return (i.e., low testing soils and crops with high P response).

The process of P fertilizer allocation involves a number of steps:

1. determining the P fertilizer recommendations for the crops within each SLC polygon,
2. adjusting for the relative fertilizer expenditures within each class of farming operations,
3. adjusting for the relative fertilizer expenditures within each ecozone, and
4. balancing these adjusted recommendations to match the reported P fertilizer shipments to each province each year.

Areas of each crop within each SLC polygon are provided from allocations of census crop areas to SLC polygons by Statistics Canada and retained in a centralized Sustainability Metrics database. This ensures that all national agri-environmental indicators are using a common land area database. Fertilizer recommendations are calculated from provincial P fertilizer recommendation tables that have been converted to linear equations for each crop, using the predicted STP concentrations (outlined below) for each polygon. These equations have been modified so that the minimum fertilizer recommendation for any crop is one half of the lowest non-zero recommendation (so no polygon has a zero recommendation for P). This modification accounts for farmers that apply a small amount of starter P fertilizer regardless of the STP concentration, and for the areas within the polygon that have lower STP concentrations than the average and require additional P for optimum crop production. The recommendations for all of the crops within each SLC polygon are summed to give a total P recommendation for each polygon, as shown in eq. 1.

Table 3. North American Industrial Classification System categories used to segregate fertilizer expenditures for different farming systems.

Category no.	Category
1	Dairy
2	Beef
3	Hog
4	Other livestock
5	Poultry
6	Field crop
7	Field vegetable
8	Other crops

$$\text{Total P recommendation} = \sum_{i=1}^{n} (\text{CropArea}_i \times \text{FertRecc}_i) \quad (1)$$

where n is the number of crops (i) within each SLC polygon, CropArea_i is the area of crop i in hectares, and FertRecc_i is the P fertilizer recommendation for crop i in kg ha^{-1}. The STP concentration for each SLC polygon is updated each year based on the cumulative P balance for previous years.

The adjustment for relative fertilizer expenditures is based on the farms within different North American Industry Classification System (NAICS) categories (Kelton et al. 2008). This separates farm operations into classes dominated by different production systems, including the segregation between livestock and non-livestock farms as well as among different types of livestock. This classification of farm areas is derived from the Census of Agriculture data on a census division (CD) scale (Statistics Canada 2017). The list of categories used in this exercise is shown in Table 3. Category 8 includes fertilizer that was applied to non-field crops (e.g., greenhouses or container nursery crops), so the proportion of fertilizer expenditures in this class was removed from the total fertilizer expenditures. Relative fertilizer expenditures for each NAICS category are calculated for each province, by dividing the average fertilizer expense per hectare in the province by the fertilizer expense per hectare in each category. This relative expense is then used to adjust the fertilizer recommendations in the SLC polygons within each CD for the reductions in fertilizer P due to manure applications, as well as other factors that influence fertilizer purchase decisions by farmers in each category, such as cash flow.

Fertilizer applications also vary with the broader biophysical conditions which drive differences in productivity and in the characteristics of farms within each NAICS category. The ecozones of Canada are used as indicators of this ecological variation; thus, the P fertilizer shipments within each province are divided among ecozones within the province according to the proportion of total fertilizer expenditures within each ecozone.

$$\text{(2)}\quad \text{P shipments in each ecozone (kg)} = \text{P shipments in province (kg)} \times \frac{\sum \text{Fertilizer expenses (\$) in CDs within ecozone}}{\sum \text{Fertilizer expenses (\$) in entire province}}$$

The adjusted P fertilizer recommendations within each SLC polygon are then corrected, so they match the total P shipments allocated to each ecozone and province, as a prediction of fertilizer allocated across the agricultural landscape.

$$\text{(3)}\quad \text{P allocated to SLC polygon (kg)} = \text{P recommended for polygon (kg)} \times \frac{\text{Actual P shipments in ecozone (kg)}}{\sum \text{P recommended for polygons within ecozone (kg)}}$$

Phosphorus removal in the harvested portion of the crop is calculated by multiplying the crop yields by the P concentration in the harvested portion of each crop [International Plant Nutrition Institute (IPNI) 2016]. Phosphorus concentrations in crops are assumed to be constant across the SLC polygons, as data on regional differences in tissue P concentration was not available, and any small-scale variation will be averaged out across the areas of the various crops. This assumption may result in an underestimation of P removal from soils with high levels of P due to luxury consumption, but the impact is expected to be minor. The P contents for each crop (kg) are summed to give the P removal from each SLC polygon (eq. 4).

$$\text{(4)}\quad \text{P removal (kg)} = \sum_{i=1}^{n} (\text{CropArea}_i \times \text{Yield}_i \times \text{Pyield}_i)$$

where CropArea_i is the area of crop i within a SLC polygon (ha), Yield_i is the harvested yield of crop i (kg ha^{-1}), Pyield_i is the P concentration of the harvested portion of crop i (kg P kg^{-1} yield), and n is the number of crops within the SLC polygon.

P balance calculation

Calculation of the P balance for each SLC polygon is now simply a matter of adding the P inputs from mineral fertilizer and manure and subtracting the P removal to determine the net P addition (or deduction) for the individual SLC polygon. This value is then divided by the total area of crops and improved pasture to calculate the P balance per hectare (eq. 5).

$$\text{(5)}\quad \text{P balance (kg ha}^{-1}) = (\text{manure P (kg)} + \text{fertilizer P (kg)} - \text{crop P removal (kg)}) / (\text{hectare of crops and improved pasture})$$

1961–1980 historic P balance calculation for Ontario

To address the issue of large mineral fertilizer P inputs in the province of Ontario during the two decades prior to 1981 (Bruulsema et al. 2011), P balance calculations were completed for this period. This was not done for the other provinces because the predicted P accumulations matched the measured STP concentrations much more closely than did Ontario's (van Bochove et al. 2012) and because the data on fertilizer shipments in other provinces was not available. The initial STP concentrations for Ontario had been adjusted upwards in the agri-environmental indicators report No. 3 to account for the difference between predicted and measured (van Bochove et al. 2010*b*), but it was done by increasing all of the initial STP concentrations in the province by the same value, so regional differences in fertilization patterns were not accounted for. Data for crop areas, crop yields, and livestock manure productions during the 1961–1980 time period were compiled at the scale of geographic county area (Queen's Printer for Ontario 1962–1981), as they were not available at the SLC polygon scale, for use in P balance calculations. Aside from the difference in the spatial unit, the P balance calculations were consistent with the later time period with the following exceptions.

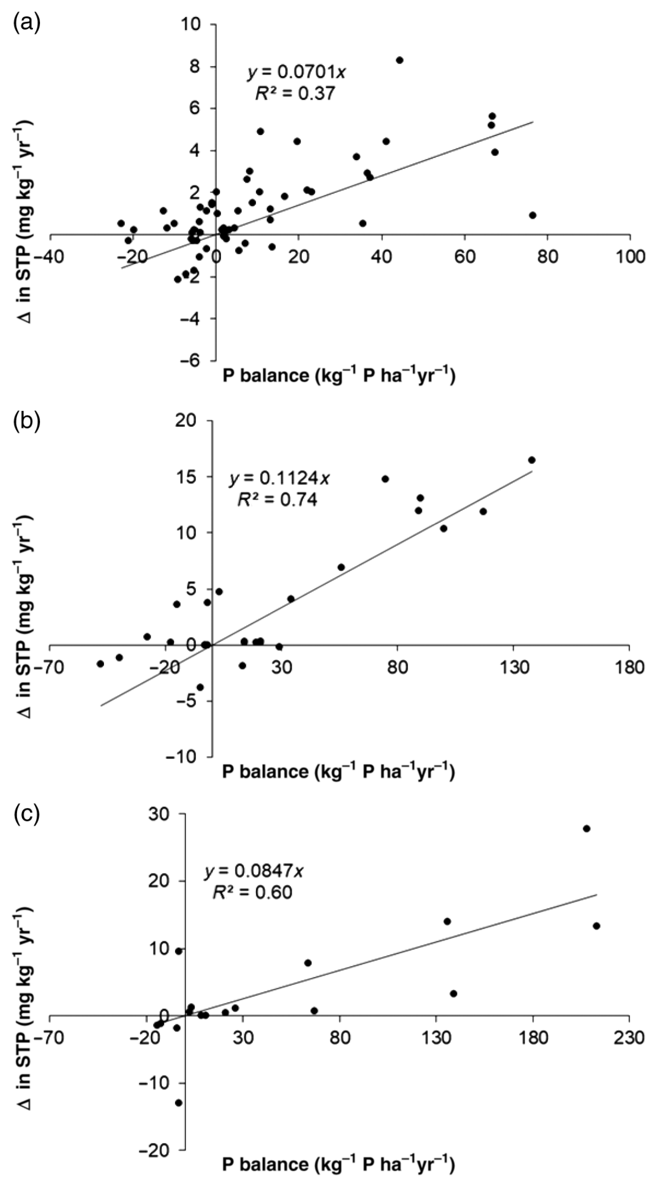
- Manure N and P allocation using the CANB model was not available, so P excretion from livestock was estimated using the ASABE table values for manure P excretion per 1000 kg of animal live weight (ASABE 2005).
- Fertilizer expenditure data were not available, so adjustment for differences in fertilizer expenditures by different farming systems was done using the proportions calculated for the 1981 census year.
- Allocation of fertilizer P shipments to ecozones was assumed to follow the same proportions as in 1981.

The calculated P balances per hectare were summed for each year from 1961 to 1980, and this cumulative P balance for each county is used to estimate median STP concentrations for each county. These, in turn, are used as initial STP concentrations for the SLC polygons within each county in 1981.

Estimated soil test P calculation

A literature review of studies that had measured a change in STP over time and had sufficient data to calculate P balance was conducted. The selection criteria for including studies in our meta-analysis included (*i*) that they be conducted on Canadian agricultural soils or soils from the Northern USA having similar soil characteristics to the Canadian regions being assessed, (*ii*) that the study be a minimum of 6 yr in length to allow for STP changes to be more reliably detected (We noticed more variability in our data using studies <5 yr, data not shown), (*iii*) that STP concentrations were determined on soil samples from about the top 0–15 cm and determined using the same sampling protocol at the onset and completion of the study, and (*iv*) data on P inputs (as mineral fertilizer or animal manure) and P outputs (i.e., crop yield and P content) were available. In one case where crop P removal data were not available, data from the nutrient uptake and removal by field crops for eastern Canada (Canadian Fertilizer Institute 1998) were used to estimate crop P removal. A summary of the studies included in developing the relationships predicting changes in STP from P balance for each of Olsen, Mehlich 3, and modified Kelowna soil tests are included in Supplementary Tables S1, S2, and S3.[1] For calculating the linear relationships between P balance

Fig. 2. Linear relationships derived from the literature showing the change in soil test phosphorus (STP) concentrations (mg kg^{-1} yr^{-1}) for (*a*) Olsen, (*b*) Mehlich 3, and (*c*) modified Kelowna STP as affected by the mean annual P balance (kg P ha^{-1} yr^{-1}).



in kg ha^{-1} yr^{-1} and change in STP concentration in mg P kg^{-1} yr^{-1}, one value from Stumborg and Schoenau (2008) with a high P balance of 164 kg P ha^{-1} yr^{-1} was excluded from the analysis. Similarly, for the modified Kelowna soil test, P balances greater than 300 kg P ha^{-1} yr^{-1} were also excluded [see, for example, Miller et al. (2011) and Olson et al. (2010)]. These data were excluded because they were much higher than the P balances observed for the SLCs in those regions and were affecting the fit of the linear relationship for the range of interest.

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjss-2019-0023.

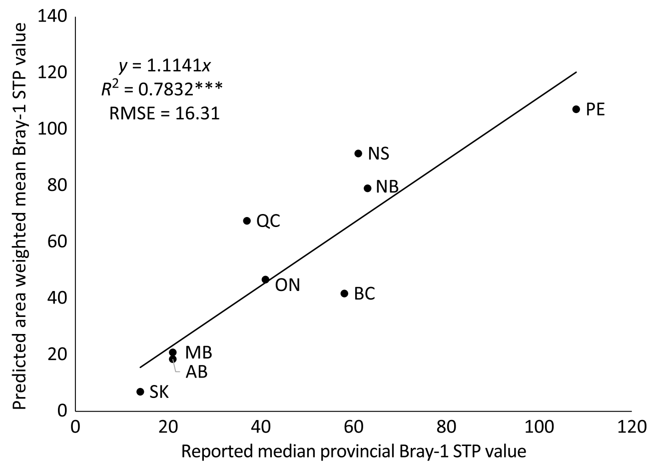
Median STP concentrations for each SLC polygon were calculated by assuming a linear relationship between change in STP and the cumulative P balance, and that all areas of the country started out with a low STP concentration prior to agricultural intensification of P use (Table 1). These relationships are unique to each of the soil test methods that are used in different provinces across the country and are shown in Fig. 2. A minimum concentration of 1 mg kg^{-1} was set for each STP, so that areas with negative P balances did not predict a negative STP concentration, which would be a physical impossibility.

For provinces outside of Ontario, where cumulative P balances were not calculated prior to 1981, the annual P balances were estimated by interpolating back from 1981 to an assumed balance of zero in 1976, consistent with the approach of van Bochove et al. (2012). The STP concentrations were calculated each year and used as the starting point for estimating P fertilizer recommendations for the following year.

Validation data

Data to validate the modeling of P accumulation was collected from various sources. The International Plant Nutrition Institute reports provincial median STP concentrations once every 5 yr (IPNI 2016), and these data were extracted for 2010 to compare with the modeled values based on the 2011 census year. Model predictions were converted to Bray P1 equivalents to match the values in the IPNI report, using the conversion coefficients reported by IPNI (2016). Aggregate Olsen STP data by county was provided for Ontario by SGS Agrifood Labs (Guelph, ON, Canada), with sample numbers ranging from 2 to 4440 per county. Only data from counties with >100 samples were included in the analysis, and these were compared with the area-weighted mean predicted STP concentrations for the SLC polygons within each county. Aggregate Olsen STP data by postal code were provided by AgVise Laboratories (Northwood, ND, USA) for Manitoba, which was compared with the area-weighted mean predicted STP concentration for the SLC polygons within each postal code area. Field STP concentrations were provided by the Prince Edward Island Department of Agriculture & Fisheries, Sustainable Agriculture Section, who conduct an annual survey, and the median of the reported Mehlich 3 STP concentrations for 2009–2013 within each SLC polygon were compared with the predicted values for those polygons. Modified Kelowna STP concentrations for parts of British Columbia were extracted from reports of STP concentrations within the Fraser and Okanagan valley areas (Kowalenko et al. 2007; Kowalenko et al. 2009; Sullivan and Poon 2016) and compared with predicted concentrations for those areas in the reporting years. Outliers in the data were determined by visual inspection and by calculating robust Z-scores for each of the data points. Points with Z-scores >3.5 were excluded

Fig. 3. Comparison of predicted area-weighted mean soil test phosphorus (STP) concentrations to reported STP concentrations by province in 2010, all converted to Bray P1 concentrations (IPNI 2016). RMSE, root-mean-square error.



from the statistical analysis but were shown on the charts as outliers; all of the outliers had Z-scores >>3.5.

Statistical analysis

Analysis of variance and regression statistics (R^2 and root-mean-square error) were calculated using the Data Analysis Pak in Excel. Regression analysis was used to determine if the slope and intercept were statistically significant ($p = 0.05$); where the intercept was not significant, the slopes were re-calculated through a zero intercept. Residual values from the regressions were checked, and no bias was apparent. Algorithms to calculate cumulative P balance were coded in Python version 2.7, and maps were prepared using ArcGIS version 10.4.1 (ESRI 2011).

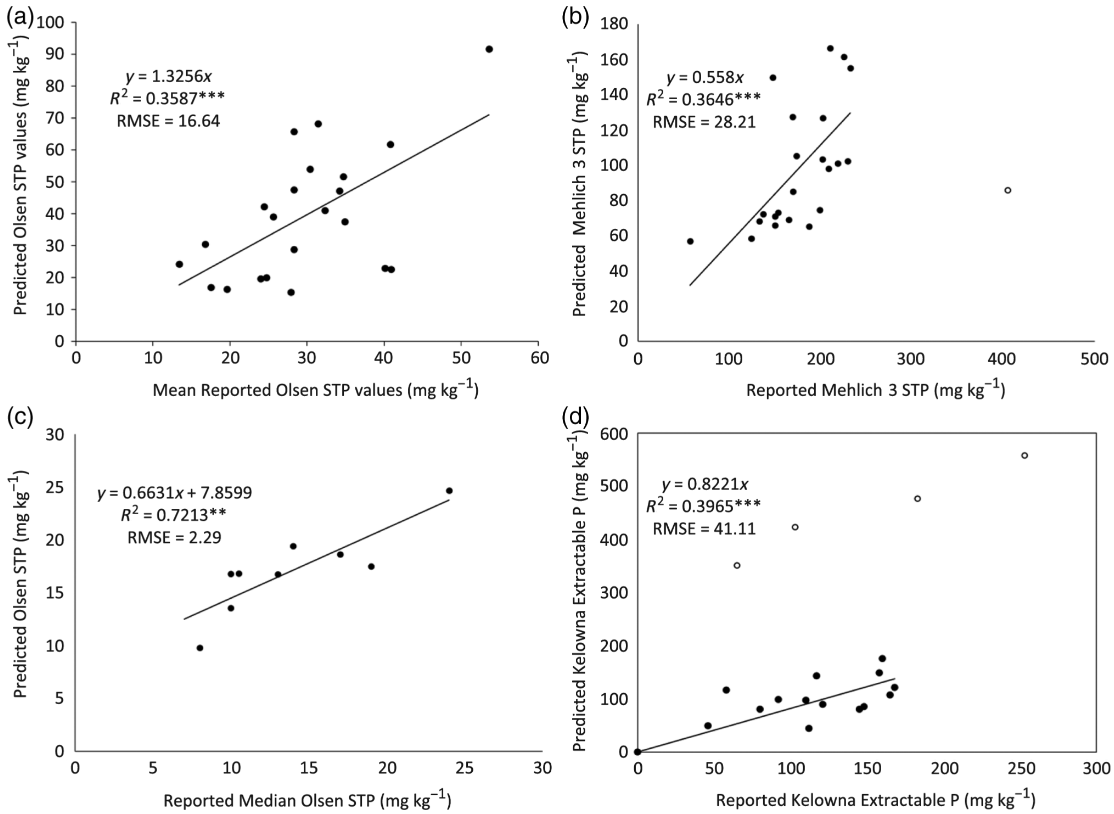
Results and Discussion

Limitations of P balance estimations

The calculated P balance has several potential sources of error, and so can only be an indicator of trends. The allocation of mineral fertilizer P according to crop requirements and modified by relative fertilizer expenditures assumes that all fertilizer decisions are completely rational, which we know is not the case for any purchasing decision. Furthermore, although the assumption that manure P stays where it is generated may be broadly correct, it ignores the possibility of manure transport to other areas, or the diversion of manure to non-agricultural purposes (e.g., potting mixes). We have been unable to find any statistics regarding these types of transfer, and so they have been ignored in this analysis.

The reported STP concentrations used to validate our model are also imprecise. Not all fields are sampled each year, or with the same frequency, so there may be an inherent bias in the reported data with a greater or

Fig. 4. (*a*) Comparison of area-weighted mean 2011 predicted Olsen soil test phosphorus (STP) concentrations by county in Ontario to mean reported Olsen STP concentrations. (*b*) Comparison median 2011 predicted Mehlich 3 STP concentrations in Prince Edward Island to median reported Mehlich 3 STP concentrations. One outlier value was excluded from the analysis. (*c*) Comparison of area-weighted mean 2011 predicted Olsen STP concentrations by postal code in Manitoba to median reported Olsen STP concentrations. (*d*) Comparison of area-weighted mean 2011 predicted modified Kelowna STP concentrations by township in British Columbia to median reported modified Kelowna STP concentrations. The outlier values (open circles) were excluded from the analysis as they represent large livestock operations on small Soil Landscape of Canada polygons, where the amount of manure export is unknown but expected to be high. Significance of the regression equation is represented by asterisks after the R^2 value (*, $P = 0.05$; **, $P = 0.01$; ***, $P = 0.001$). RMSE, root-mean-square error.



lesser proportion of low testing fields from extensive grazing systems or high testing fields from intensive livestock operations. There is also the issue of soil test results being attributed to the location of the farm headquarters, even though the land area may be spread across multiple SLC polygons.

The calculations estimating the change in STP concentration from the P balance may also introduce some error as the change in STP can be affected by soil properties that affect phosphorus availability as well as by the type of added P (Shigaki and Sharpley 2011).

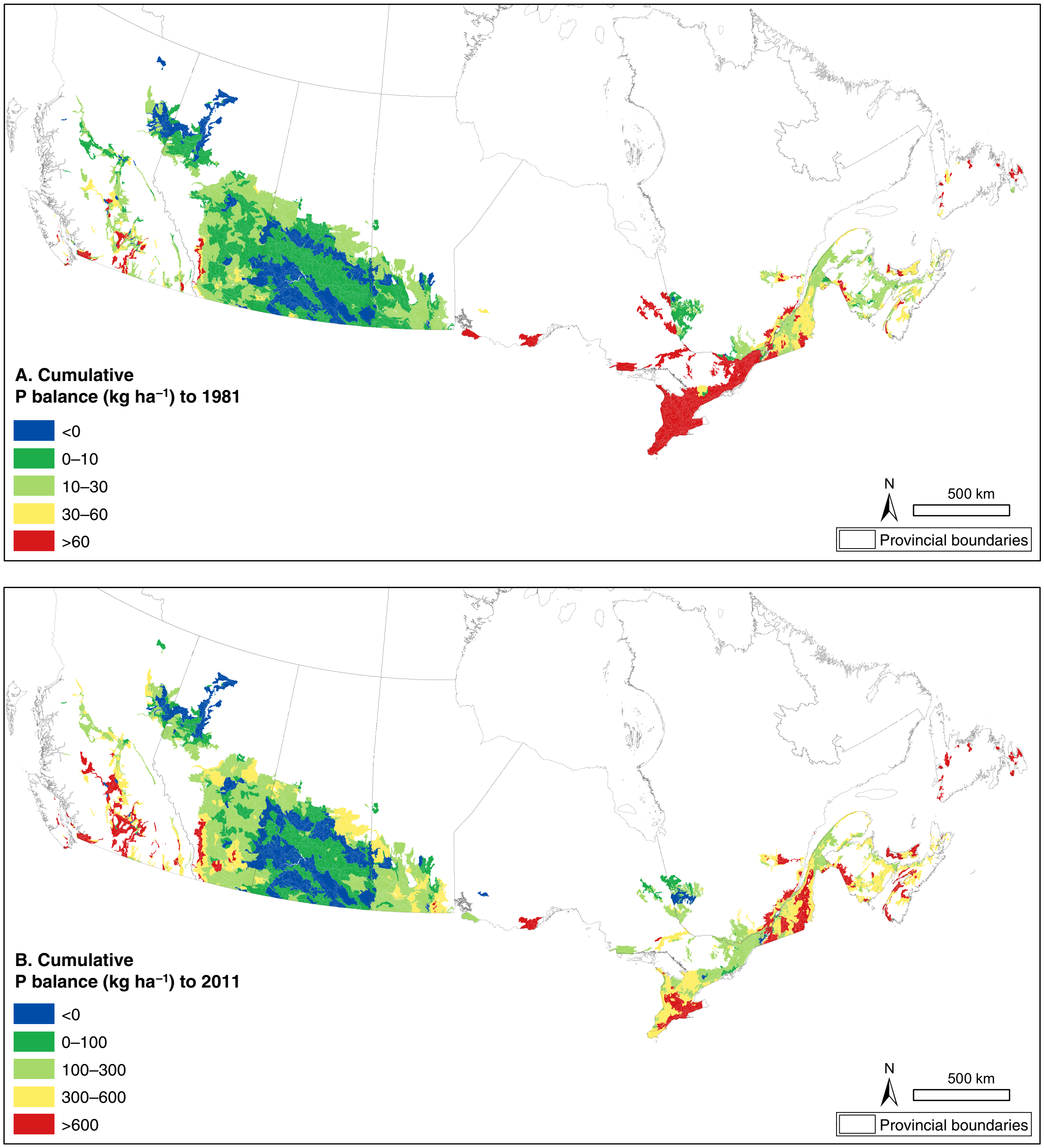
Despite these limitations, there is strong evidence that the revised method of predicting cumulative P balance, and from that, STP, is valid for Canadian agricultural areas. The consistent pattern of correlations between the predicted and reported STP levels across a range of provinces using different soil test extractants, and a range of production systems, suggest that the predicted values are largely reflective of average field conditions.

Validation of STP predictions against reported values

The comparison of median predicted STP concentrations to reported concentrations at the provincial scale are shown in Fig. 3. This relationship showed a strong R^2 of 0.78, with an intercept of zero and a slope that was slightly positive but not significantly different from 1. The relationship was similar to that shown by van Bochove et al. (2012) for 2006, with the exception that predicted values for Ontario now lie much closer to the 1:1 line. This is to be expected, because both models allocate provincial total manure and fertilizer P within each province, and any differences due to the updates of the model would show up at the subprovincial scale.

Figure 4 shows the correlations between the predicted and reported STP data for the four provinces where validation data were available at a finer scale. In all cases, there was a significant positive correlation between the predicted and reported values, with R^2 values ranging from 0.36 to 0.72. All of the provinces except Manitoba

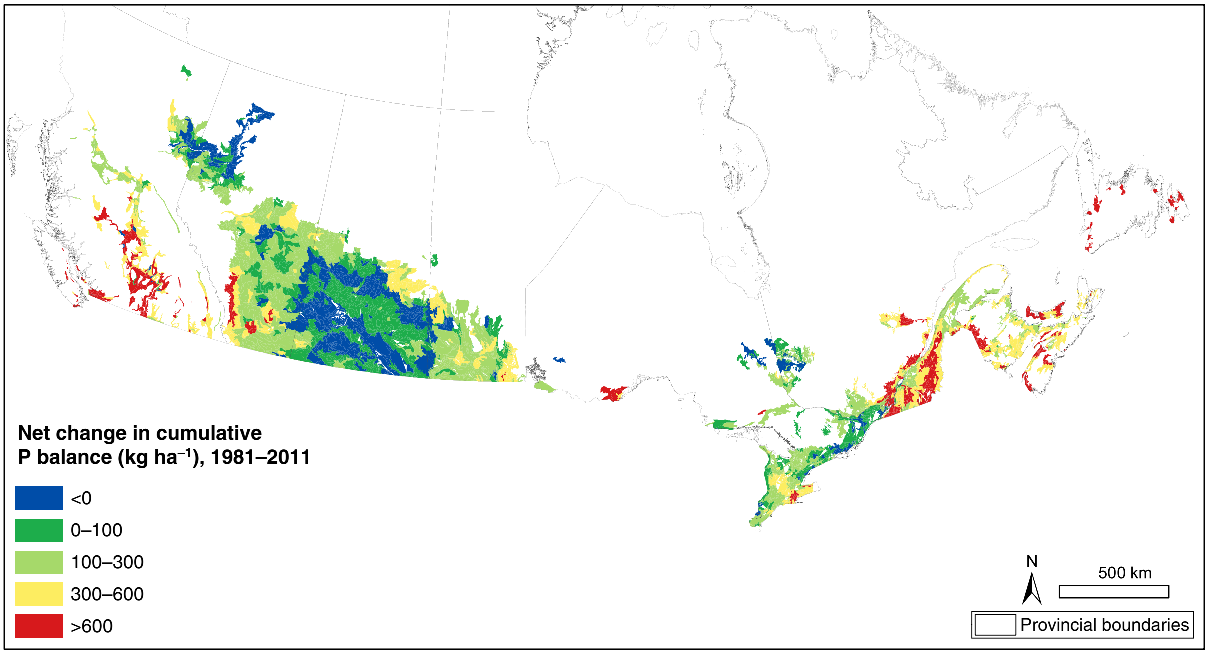
Fig. 5. Cumulative phosphorus (P) balance (kg ha^{-1}) for Soil Landscape of Canada polygons for (A) the period from 1976 to 1981 (except Ontario, which is from 1961 to 1981) and (B) the period from 1976 to 2011 (except Ontario, which is from 1961 to 2011).



had intercepts which were not significantly different from zero. The slope for Ontario was slightly greater than 1, indicating a trend to over-predict STP concentrations at higher values. The other three provinces had slopes that were <1, although in the case of British Columbia, the slope was not significantly less. The greatest discrepancy was in the case of Prince Edward Island, where the STP concentrations from the provincial survey were roughly double that estimated by the cumulative P balance. This may be due to inaccurate assumptions regarding the starting concentrations for STP in 1976 (the beginning of the modeling period), or to preferential sampling of potato fields, which tend to have high STP concentrations (Boiteau et al. 2014), over other types of crops. In support of our hypothesis, the provincial STP levels recorded in the IPNI survey were closely aligned with the predicted values, and did not show the large increase.

In both British Columbia and Prince Edward Island, there were outliers which were excluded from the comparison. In the case of British Columbia, the outliers were SLC polygons in the lower Fraser Valley which had small land areas but were home to large dairy or broiler chicken operations. In discussion with local specialists, it was

Fig. 6. Net change in cumulative phosphorus (P) balance (kg ha^{-1}) from 1981 to 2011 for the agricultural regions of Canada.



determined that manure from these operations was largely exported, either to other parts of the Fraser valley or across the international border into Washington State, but there were no statistics available that indicate the amount of movement that occurred. The reason for the outlier in Prince Edward Island was less clear, other than the dominance of potato production in a small area in Eastern PEI, but because the outlier was approximately double the STP of all the other SLC polygons on the island, it was excluded from analysis.

Spatial distribution of cumulative P balance

The spatial distribution of predicted P accumulation in Canadian soils (kg P ha^{-1}) is shown in Figs. 5 and 6. Note that the categories of P accumulation are different for Fig. 5*a* than for Figs. 5*b* and 6. The impact of extending the period for the P balance calculation to 1961 in Ontario is evident in Fig. 5*a*, with almost all of the SLC polygons in the province showing a net accumulation of >60 kg P ha^{-1} by 1981. This illustrates the importance of including the earlier time period in the analysis for Ontario. There are pockets across the country with similar levels of P accumulation prior to 1981, primarily in southern Quebec, southwestern Alberta, southern British Columbia, and Prince Edward Island, whereas most of the country is closer to a balance between P application and removal. Large areas of P deficit in the Prairie provinces are also evident, extending up into the Peace River district in northern British Columbia.

The pattern shifts somewhat for 2011, particularly in Ontario and Quebec (Fig. 5*b*). In southern Ontario, the areas of highest P accumulation are along the north shore of Lake Erie (i.e., coinciding with regions dominated by poultry production in Niagara, tobacco and field horticulture on the Norfolk sand plain, and mixed field horticulture further west), and then north into mid-western Ontario where there is a high density of swine and dairy farms (Statistics Canada 2017). In southern Quebec, the pockets of swine production in south of Montreal and of dairy production in the Eastern Townships show up as areas of high P accumulation. The areas of high P accumulation have expanded in the Atlantic provinces, which can be attributed to broiler chickens and potatoes in western New Brunswick, potatoes in Prince Edward Island, and mixed horticulture and livestock in the confined areas of arable land in Nova Scotia and Newfoundland. Large areas of P deficit are still evident in the Prairie provinces, but this has lessened in Manitoba and Alberta. The area of high P accumulation in "feedlot alley", which agrees with the high concentrations of intensive beef finishing operations in southwestern Alberta (Beaulieu et al. 2001) has expanded. British Columbia shows several areas of high P accumulation where agricultural production is concentrated in valleys (where there is limited opportunity for nutrient export), with the highest build-up in the Fraser valley just east of Vancouver.

The net change in the cumulative P balance from 1981 to 2011 (Fig. 6) shows similar patterns to the total accumulation by 2011, but it does highlight the areas that have continued to apply P in excess of crop removal. The biggest contrast is in southern Ontario and southwestern Quebec, where the rate of P accumulation since 1981 has been more modest than prior to that. The only area showing high P accumulation since 1981 in southern Ontario is the Norfolk sand plain, where tobacco production has only recently been replaced by field vegetables. The areas dominated by cash crop production have shown P applications that are much closer to balance, or even in slight deficit.

Conclusions and Further Work

The revised method for predicting P accumulation, and the resulting STP, appears to correlate reasonably well with the reported values for STP in several regions across Canada. Canadian agricultural soils have accumulated significant quantities of P over the past three decades, most notably in areas with high livestock density. These areas represent a potential long-term source of P that could desorb into runoff water and adversely impact the quality of downstream freshwater. There is evidence that measures are being taken in some areas to draw down this reserve, but this is related more to regions dominated by cash crop production than to areas accumulating excess P from livestock manure. Addressing the surplus P from high concentrations of livestock poses many challenges, and it may only be solved by significant relocation of livestock operations (Reid et al. 2019). At the same time, there are still significant areas of P deficit that will require the application of supplemental P to optimize crop production. In these areas, the focus should be on application timing and method so the incidental losses from applied P are minimized (Reid et al. 2018).

This accumulated P represents the store of P potentially available for loss and is generally an indicator of system sustainability (Sharpley et al. 2012; Johnston et al. 2014), but it is not automatically a risk to water quality. This assessment needs to be combined with estimates of the proportion of the accumulated P which is likely to desorb (based on soil texture and soil pH), and the potential for runoff from each SLC polygon to surface water. The cumulative P balance and predicted STP concentrations will form a key input into the revised IROWC-P.

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