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Indicator of risk of water contamination by phosphorus (IROWC-P)

A Handbook for using the IROWC-P algorithms

Canada

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A Handbook for presenting the IROWC_P algorithms

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A Handbook for presenting the IROWC_P algorithms

This work was part of the AAFC "National Agri-Environmental Health Analysis and Reporting Program" (NAHARP) under the Federal/Provincial/Territorial Agricultural Policy Framework (2003-2008).

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Section 1 – IROWC_P General Algorithm

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Introduction

The purpose of this handbook is to present in one document the equations, data sources, references and limitations associated to each component of the Indicator of Risk of Water Contamination by Phosphorus (IROWC_P). The indicator is focusing exclusively on the risk associated with agricultural practices and was developed to be used at the Soil Landscape of Canada (SLC) and the watershed scales. Parameters impacting IROWC_P outputs that are relevant at these two scales and for which national databases are available were integrated in the IROWC_P algorithms. In addition, other parameters generally associated to larger scales (local parameters), such as preferential flows components, were also integrated because of the substantial impact they can exhibit at the SLC and watershed scales. Different types of models have been developed to simulate and evaluate management scenarios at the watershed scale. Models are often complex and require detailed parameterization data on physical, chemical and biological soil properties as well as agronomic data (Sharpley, 2007). However, site-vulnerability tools are also available to evaluate areas at greater risk for P loss based on either additive (Lemunyon and Gilbert, 1993; Bolinder et al., 2000) or multiplicative (Gburek et al., 2000) P index approaches. An Indicator of Risk of Water Contamination by P (IROWC_P) for agricultural land of Canada has been conceptualized on the basis of the multiplicative approach to integrate a water balance model and connectivity to hydrologic network at a broad watershed scale (van Bochove et al., 2006). The relevance of developing an IROWC_P for Canada is to identify critical areas across the country where more prospecting is required to protect surface water at the operational management watershed scale as well as to assess impacts of beneficial management practices (BMPs) on risk mitigation (Table 1.1).

The Indicator of Risk of Water Contamination by Phosphorus (IROWC_P) was developed to assess the temporal and spatial trends for the risk of surface water contamination by P from Canadian agricultural land at the watershed scale. IROWC_P first estimates the annual amount of dissolved phosphorus that is potentially released (desorbed) from agricultural soils (P_Source component). The P_Source component was estimated as a function of cumulative P additions and removals over a 30 year period up to 2006 and the degree of soil P saturation. IROWC_P then integrates the P_Source component through a Transport-Hydrology component that considers transport processes (surface runoff, drainage and water erosion) and hydrological connectivity (topography, tile drainage, surface drainage and preferential flow) to estimate the likelihood for P to enter streams or water bodies.

Table 1.1 Beneficial management practices (BMPs) considered in the IROWC_P algorithms that impact directly IROWC_P components or processes associated to IROWC_P components.

IROWC_P components	Processes	BMPs
P Balance	Not applicable	Phytase use (pig, poultry) Manure management Fertilization guidelines
P Transport	Soil water erosion	Soil conservation practices
Preferential flow	Burrow flow (earthworms)	Tillage practices
	Crack flow	Tillage practices

Data Sources

Data sources for IROWC_P calculations are described in the following sections of this document and are specific for each component and sub-component of the IROWC_P.

- ***P_Source***
  - P_Status
  - P_Balance
    - P_{manure}
    - $P_{mineral}$
    - $P_{removal}$

- ***Transport_Hydrology* (*T_H*)**
  - Soil erosion (E) and Delivery Ratio (DR)
  - Water balance (R & D): surface runoff (R) and drainage (D)
  - Surface drainage (SD)
  - Tile drainage (TD)
  - Topographic index (TI)
  - Preferential flow (PF)
    - Burrow flow (BF)
    - Crack flow (CF)
    - Lateral flow (LF)
    - Finger flow (FF)

General Algorithm

$$IROWC\_P = [P\_Source] * [T\_H] \tag{1.1}$$

This general algorithm aims to separate the annual risk of water contamination at the watershed scale by dissolved phosphorus (DP) and by particulate phosphorus (PP).

The total amount of DP that can be potentially desorbed from agricultural land and transported to waterbodies is quantitatively (mg L^{-1}) estimated by the P_Source component multiplied by the transport-hydrology component (Equation 1.1). The P_Source component depends on the soil P saturation and the 30-year cumulative P balance (1976 to 2006). The total amount of PP is estimated indirectly by the quantity of soil particles removed by water erosion and transported to streams as a function of the P saturation, expressed by P_Source. IROWC_P is given by Equations 1.2 and 1.3 which are not dimensionally correct at this stage.

$$IROWC\_P = [P\_Source] * [\alpha\{R(connectivity)\} + \beta\{D(connectivity)\} + \gamma\{E(DR)\}] \tag{1.2}$$

which becomes in its extended form,

$$IROWC\_P = [P\_Source] * \left[\alpha\left\{R\left(\frac{TI + SD + BF + CF}{4}\right)\right\} + \beta\left\{D\left(\frac{TD + LF + FF}{3}\right)\right\} + \gamma\{E(DR)\}\right] \tag{1.3}$$

where:

P_Source is the concentration of water extractable phosphorus (Pw, mg kg^{-1}) that can be potentially desorbed from agricultural soils in a watershed during a Census year;

R and ***D*** are surface runoff and deep drainage (mm water yr^{-1}) through the soil profile;

TI, ***SD***, ***BF***, ***CF***, ***TD***, ***LF***, and ***FF*** are dimensionless connectivity factors with values rescaled between 0 and 1;

E[1] is the quantity of eroded soil particles transported by water within agricultural fields (kg ha^{-1} yr^{-1});

DR is the proportion (%) of sediments delivered from agricultural fields to streams at the watershed scale;

α, ***β***, and ***γ*** are regression coefficients obtained from multiple regression analysis used for IROWC_P calibration (see Section 3: Transport-Hydrology).

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[1] In the future, respective proportions of PP and bio-available PP in eroded soil particles have to be defined for each SLC soil series or each region to estimate amounts of PP at risk for water contamination.

In order to avoid an artificial disproportion between surface runoff and erosion in the IROWC_P model, due to their different dimensional values, the three components of T_H (Equation 1.2) are normalized (*R* and *D*) with the maximal Soil Landscapes of Canada[1] (SLC) precipitation (mm water yr^{-1}) in Canada, and the critical threshold for soil water erosion (6 t ha^{-1} yr^{-1}), to provide values between 0 and 1.

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[1] Soil Landscapes of Canada: National series of broad-scale (1:1 million) soil maps containing information about soil properties and landforms.

Section 2 – P_Source

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Summary

The environmental risk of P fertilization may be assessed by several methods including, soil test P (STP) (Sims, 1993), P sorption capacity (PSC) (Bache and Williams, 1971; Syers et al., 1973), and soil P saturation (PSI) (Sharpley, 1995; Giroux and Tran, 1996). The soil test P is the most commonly used method of identifying soils with elevated P concentrations that can affect water quality; these routine tests are inexpensive and correlate well with soluble and bioavailable P (Sims et al., 2000). However, soil testing alone cannot characterize the transport processes associated with surface and subsurface P losses. In Canada, many different tests are used to determine plant available P. The Mehlich-III analysis (M-III) is often used for acidic to neutral soils in Quebec and the Maritimes, Olsen extractions are used mainly in Ontario and Manitoba, and the Kelowna P-test is used in the western provinces (Saskatchewan, Alberta, and British Columbia) where soils are variable (calcareous class of parent material).

The characterisation of water soluble P (P_w) (Self-Davis et al., 2000; Sissingh,1971) represents a great improvement; by relating the different STP or PSI values to a general P desorption value, the status of P fertility is integrated with the sorption capacity of the soil. All Canadian soils can therefore be compared uniformly.

P_Source rationale

Phosphorus mobility in soil was first estimated by the Dutch with the development of the degree of P saturation (DPS). Van der Zee et al. (1987), followed by Breeuwsma and Silva (1992), defined the DPS as the ratio of P adsorbed on iron and aluminium oxyhydroxydes, which is extracted by acid ammonium oxalate (P_{ox} expressed in mmol kg^{-1}), over the total capacity of P sorption (PSC also expressed in mmol kg^{-1}) (Equation 2.1):

$$DPS(\%) : \frac{P_{ox}}{PSC} * 100 \qquad (2.1)$$

Van der Zee *et al.* (1987) reports that Beek (1979), Beek *et al.* (1980), and van der Zee and Riemsdijk (1986) demonstrated that the PSC, expressed in mmol kg^{-1}, is proportional to the sum of iron and aluminium extracted by acid ammonium oxalate ($Fe_{ox} + Al_{ox}$), expressed in mmol kg^{-1}:

$$PSC : \alpha_m(Fe_{ox} + Al_{ox}) \tag{2.2}$$

The proportionality coefficient α_m represents the coefficient of maximum saturation by sorption or fixation (on average = 0.5 for all soils). Considering Equations 2.1 and 2.2, DPS can be written as:

$$DPS(\%) : \frac{P_{ox}}{\alpha_m(Fe_{ox} + Al_{ox})} \tag{2.3}$$

To maintain a maximal concentration of 0.10 mg L^{-1} orthophosphates in runoff water, Breeuwsma and Silva (1992) proposed a critical DPS value of 25%, which represents the threshold value where the risk of water contamination by P becomes unacceptable.

Numerous methodologies have been developed to estimate the DPS and are called phosphorus saturation indices (PSI). The main objective of a PSI is to use common soil laboratory analyses done on a routine basis to estimate the DPS. More recent environmental indices, phosphorus desorption indices (PDI), estimate the amount of P in the soil solutions that are at risk of being transported by runoff water. One group of these PDI is known as the index of water extractable phosphorus, or P_w, because water is the only extractible constituent. The advantage of this method is that the results can be used to describe different soil types thus integrating the variability of the Canadian agricultural soils. Figure 2.1 shows the hierarchy between the three environmental indices (DPS, PSI and PDI0, several PSI related to group of soils and three major PDI.

In Quebec, a P_w indicator, noted $P_{Sissingh}$ (ratio soil/water: 1/60) (Sissingh, 1971), has been related to a phosphorus saturation index (P/Al M-III) and used to evaluate the bioavailability of P for crops and the potentially available P for transport in drainage water (Table 2.1). The critical environmental value reported for $P_{Sissingh}$ is generally admitted to be 9.7 mg kg^{-1} which corresponds to a DPS of 25%. Although all environmental regulations concerning P in Quebec are based on $P_{Sissingh}$, the time and manipulations required with this method may make it unsuitable for routine laboratory analysis. Another $P_{w,}$ noted as $P_{Self\text{-}Davis}$ (ratio soil/water: 1/10), is used in the USA to estimate the risk of P transport because it correlates well with P concentration in drainage waters by surface infiltration (Self-Davis et al., 2000). Analysis of about 50 mineral soils from across Canada showed a strong correlation between the two P_w methods. The 9.7 mg kg^{-1} threshold ($P_{Sissingh}$) corresponds to 4 mg kg^{-1} ($P_{Self\text{-}Davis}$) as shown in Figure 2.2.

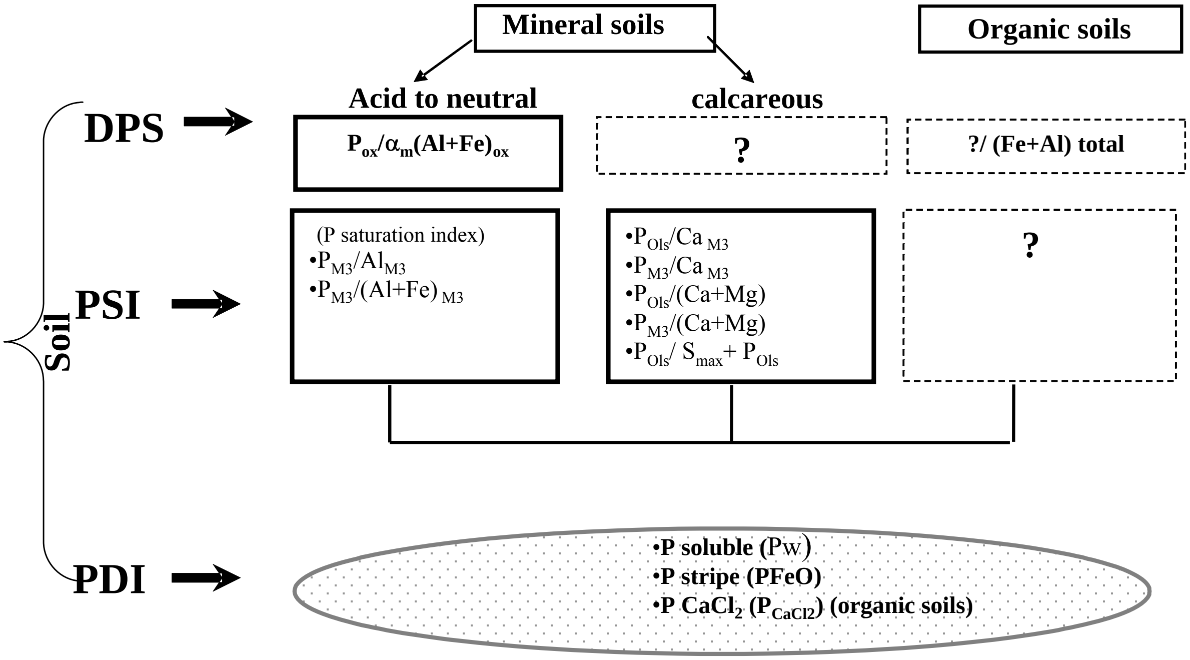

Figure 2.1. Schema of the rationale for the use of Phosphorus Desorption Indices (PDI)

Table 2.1. Environmental threshold proposed in Québec (extracted from Beaudin *et al.*, 2008)

Soils	**PSI (P/Al) M-III threshold**	**Interpretation**	**Rationale**	**Risks**	**Authors**
Histosols	5%	Environmental threshold for surface water contamination	9.7 mg Pw $_{\text{Sissngh}}$/L corresponding to 0.25 DPS$_{\text{ox}}$	Surface water contamination	Guérin *et al.*, 2007
Sandy acidic soils	11.3%	Environmental threshold for surface water contamination	9.7 mg Pw $_{\text{Sissngh}}$/L corresponding to 0.25 DPS$_{\text{ox}}$	Surface water contamination	Parent and Marchand, 2006
Acid to neutral soils		Superior limit of moderate-high fertility class and environmental risk	9.7 mg Pw $_{\text{Sissngh}}$/L corresponding to 0.10 mg Pi/L in soil solution	Surface water contamination	Pellerin *et al.*, 2006a and b
≤30% clay	7.6%				
>30% clay	13.1%				
Podzol					
0-20% clay	17%	Environmental threshold for horizontal and vertical P.flow.	9.7 mg Pw $_{\text{Sissngh}}$/L corresponding to 0.10 mg Pi/L in soil solution	Surface water contamination	Parent *et al.*, 2002
20-30% clay	12.5%				
30-60% clay	7.8%				
>60% clay	5.8%				
Gleysol					
0-20% clay	13.7%				
20-30% clay	9.7%				
30-60% clay	7.8%				
>60% clay	5.8%				
Sandy acidic soils	15%	Inferior limit of environmental risk class	0.25 DPS$_{\text{ox}}$ or 0.10 mg Pi/L in soil solution	Surface water contamination and Sub surface soil enrichment	Khiari *et al.*, 2000
Non specific	10% 20%	Inferior and superior limit of environmental risk class	250 to 600 µg P/L runoff water	Surface water contamination	Giroux and Tran, 1996

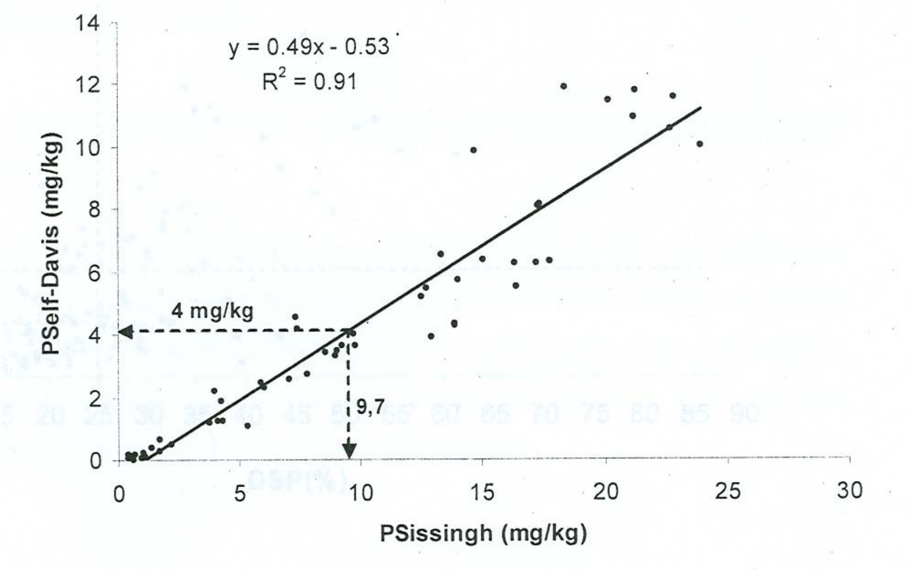

Figure 2.2. Relationship between two P desorption extraction methods

Mineral soils of different genesis, representative of soils from different provinces, were tested for P saturation using the methods $P_{\text{Self-Davis}}$ and DPS (Equation 2.3). The relationship between these two methods is presented in Figure 2.3. The critical environmental value of 25% DPS appears to correspond to the partition value between the low influence of DPS on P desorption (positive quadrant I) and the high influence of DPS on P desorption (positive quadrant II).The desorption of P is proportional to the DPS for $P_{\text{Self-Davis}}$ values higher than 4 mg kg^{-1}, while there appears to be no relationship with $P_{\text{Self-Davis}}$ values lower than 4 mg kg^{-1}. It is important to note, however, that below 2 mg kg^{-1} the mobility processes are difficult to assess and should be described as low risk.

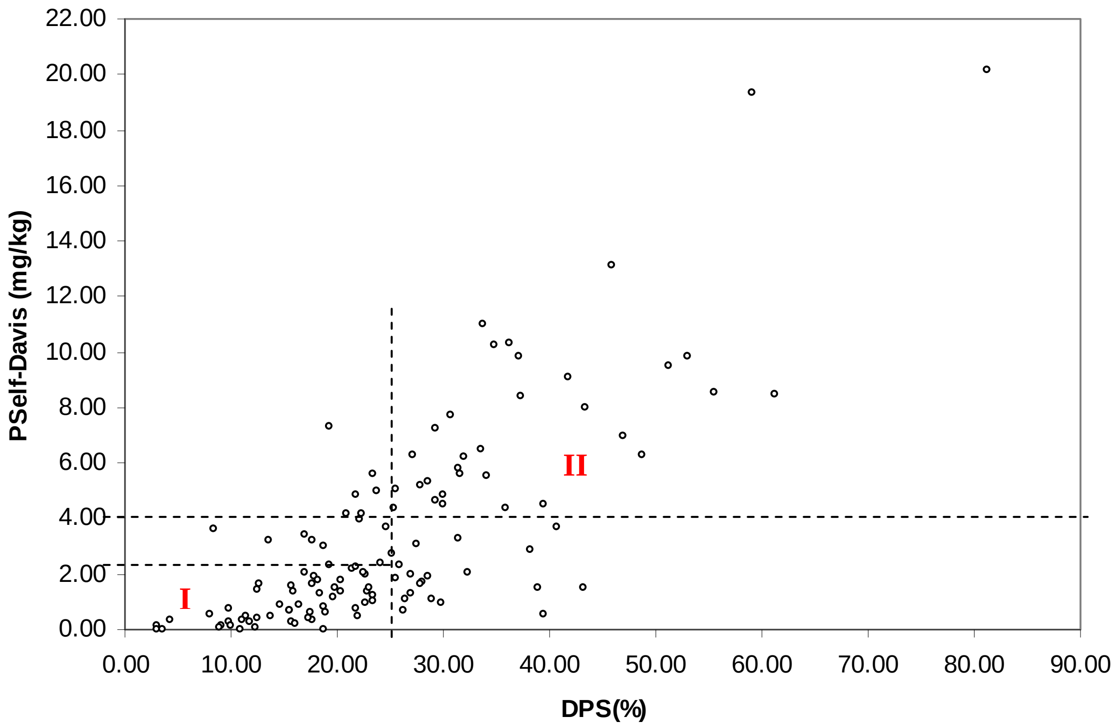

Figure 2.3. Relationship between DPS (%) and $P_{\text{Self-Davis}}$ for acidic to neutral soils in Canada

Water extractable P (P_W) used to determine the potential for soils to release P in soil water (runoff and leaching) is also correlated with soil test phosphorus (STP) and phosphorus saturation indices (PSI). However, STP and PSI values are not currently available for all regions of Canada because in most provinces STP and PSI are analyzed and compiled by private soil laboratories. In fact, STP values were only available in Quebec for the 1996 to 2001 period. (Beaudet, 2003). STP or PSI values are therefore estimated for all SLC polygons and converted into $P_{Self\text{-}Davis}$ to assess the risk of water extractable P to be release in runoff and leaching waters.

Data sources

- Phosphorus desorption indices
- Soil Landscapes of Canada v3.1.1
- Census of Agriculture (CoA) variables
- P_Balance for 1981–1986, 1991, 1996, 2001–2006 Census years (Section 2.1, page 27)
- STP enrichment models for different regions of Canada (Tables 2.3a and 2.3b)

- ***Classification of soil series in general P desorption index groups***

Classification of soil series was based on the textural class of the A horizon from the reported values in Soil Landscape of Canada (v3.1.1) following three tables:

1. List of agricultural Soil Landscape of Canada polygons (SLC) for NAHARP calculations (SL_AGR_EXT) (Warren Eilers, 2007, personal communication);
2. National Soil Component Table (nationalslc311cmp) (Soil Landscapes of Canada Working Group, 2007), which contains a list of soils found in each SLC;
3. National Soil Layer File (nationalslf311) (Soil Landscapes of Canada Working Group, 2007), which contains a description of each horizon or layer in a soil profile.

Attribute Name	Source Table
SL	SL_AGR_EXT
CMP	nationalslc311cmp
SOIL_CODE	nationalslc311cmp
PERCENT	nationalslc311cmp
LAYER_NO	nationalslf311
HZN_MAS	nationalslf311
KIND	nationalslf311
UDEPTH	nationalslf311
LDEPTH	nationalslf311
TSAND	nationalslf311
TSILT	nationalslf311
TCLAY	nationalslf311

- ***Methodology calculation***

1. Selection of four dominant components of each SLC using agricultural polygons;
2. Selection of mineral soil (KIND=M) top layers (LDEPTH <= 25 cm);
3. Update the lower depth reported to a maximum of 25 cm to obtain the weighted average textural class of a cultivated soil;
4. Calculate the horizon depth;

$$HorDepth = LDEPTH - UDEPTH \tag{2.4}$$

5. Calculate the weighted average for TSAND, TSILT, and TCLAY, respectively;

$$AvgSAND = \frac{\sum TSAND * HorDepth}{\sum HorDepth} \tag{2.5}$$

6. Classify the soil according to textural groups following the Canadian System of Soil Classification (Appendix 1);
7. Classify soil components into three groups (G1, G2, and G3) based on their textural classes;
    - **Group 1 (G1)**: heavy clay (HC), clay (C), clay loam (CL), silty clay loam (SiCL), silty clay (SiC), and sandy clay (SC)
    - **Group 2 (G2)**: loam (L), silt loam (SiL), silt (Si), and sandy clay loam (SCL)
    - **Group 3 (G3):** sandy loam (SL), loamy sand (LS), and sand (S).

- ***Phosphorus desorption indices***

Soils from the different provinces (Table 2.2) were classified on the basis of their most common STP used. Correlation analyses were done between STP or PSI with $P_{Self\text{-}Davis}$ for different textural classes of the A horizon. Acidic and neutral soils of Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and British Columbia were correlated with $(P/Al)_{M\text{-}III}$. Ontario and Manitoba soils were correlated with $P_{OLSEN,}$ and soils from Saskatchewan and Alberta were correlated with $P_{KELOWNA}$. Correlation analyses and the P desorption index (PDI) are presented in Figures 2.4 to 2.7.

Table 2.2. Representative soil series from Canada analyzed in the laboratory for: pH, pH-$CaCl_2$, pH-buffer, texture, organic matter, STP (M-III, OLSEN or Kelowna), Ca-Mg-K[1], P_{TOTox}, Pi_{ox}, Al_{ox}, Fe_{ox}, Mn_{ox}, and $P_{Self\text{-}Davis}$

Province	**Dataset**	**Contact name**	**Organisation**
British Columbia	42 soil series	Elizabeth Kenney	AAFC, Agassiz
Alberta	17 soil series	Wayne Pettapiece (retired)	AAFC, Edmonton
Saskatchewan	13 soil series	Alvin Anderson	AAFC, Saskatoon
Manitoba	93 soil series	Norma Sweetland and Bob Eilers (retired)	AAFC, Winnipeg
		Steve and Maria Sheppard	Ecomatters Inc., Pinawa
Ontario	202 soil	Craig Drury	AAFC, Harrow
Quebec	63 soil series	Laboratoire de pédologie et d'agriculture de précision	AAFC, Québec
		Gordon Barnett (retired)	AAFC, Lenoxville
		Nicolas Tremblay	AAFC, St-Jean-sur-Richelieu
		Denise Desrosiers	ITA, La Pocatière
		Pierre Audesse (retired)	IRDA, Québec
New Brunswick	no soil collected	--	
Nova Scotia	1 soil series	Ken Webb	AAFC, Truro
Prince Edward Island	12 soil series	Delmar Holmstrom	AAFC, Charlottetown
Newfoundland and Labrador	no soil collected	--	

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[1] Using M-III extraction for QC, NB, NS, PEI, and NF and ammonium acetate for BC, AB, SK, MB, and ON.

Four P desorption models were developed following laboratory analysis of representative soil series from Canada.

1. $P_{Self\text{-}Davis}$ vs $(P/Al)_{M\text{-}III}$ EAST

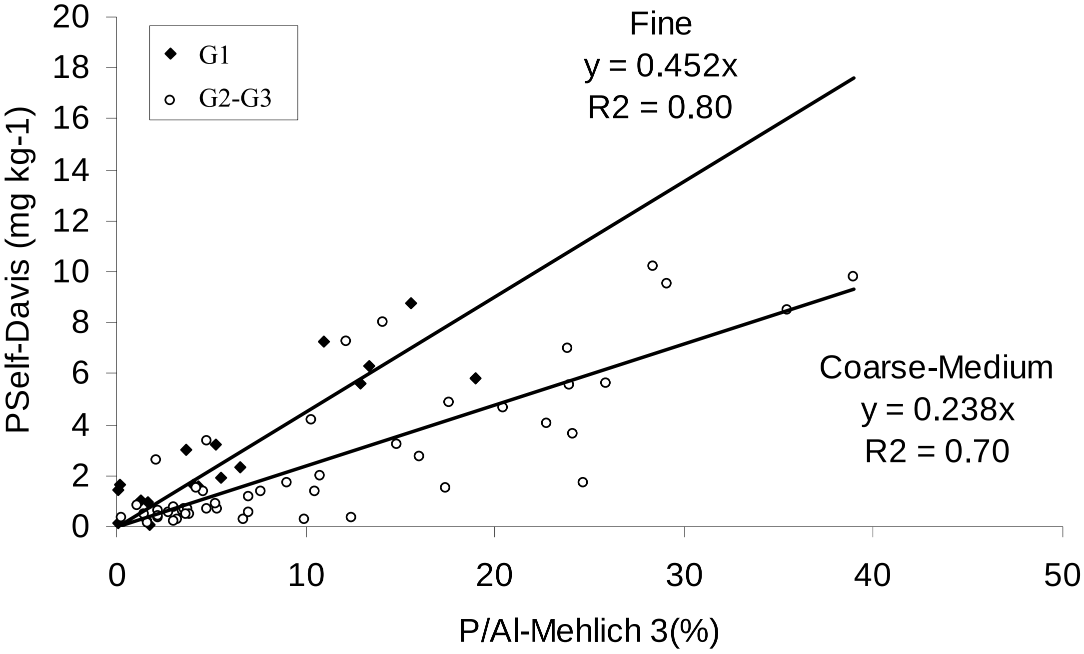

Figure 2.4. General P desorption model for PSI $(P/Al)_{M\text{-}III}$

For Eastern Canada soils extracted with the M-III test, the risk is expressed as:

- PDI=$(P/Al)_{M\text{-}III}$ EAST * 0.45 for G1
- PDI=$(P/Al)_{M\text{-}III}$ EAST * 0.24 for G2 and G3

2. $P_{Self\text{-}Davis}$ vs STP_{OLSEN}

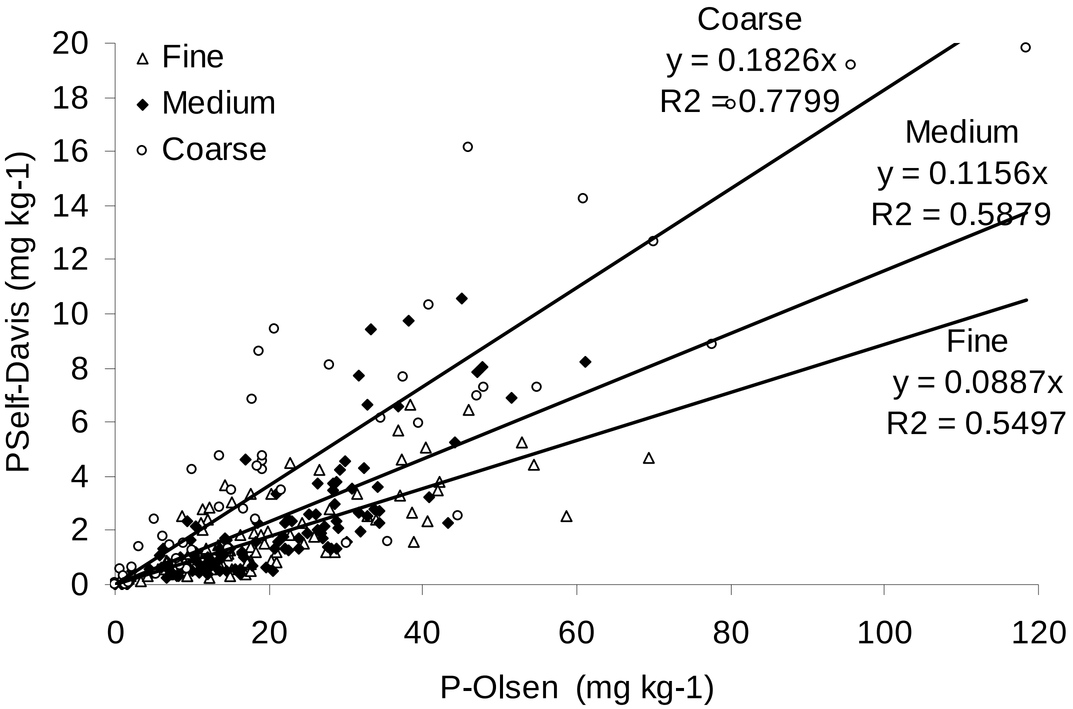

Figure 2.5. General P desorption model for STP OLSEN

For soils extracted with the OLSEN P test, the risk is expressed as:

- PDI=P_{OLSEN} * 0.09 for G1
- PDI=P_{OLSEN} * 0.12 for G2
- PDI=P_{OLSEN} * 0.18 for G3

3. $P_{Self\text{-}Davis}$ vs STP $_{KELOWNA\text{-}mod}$

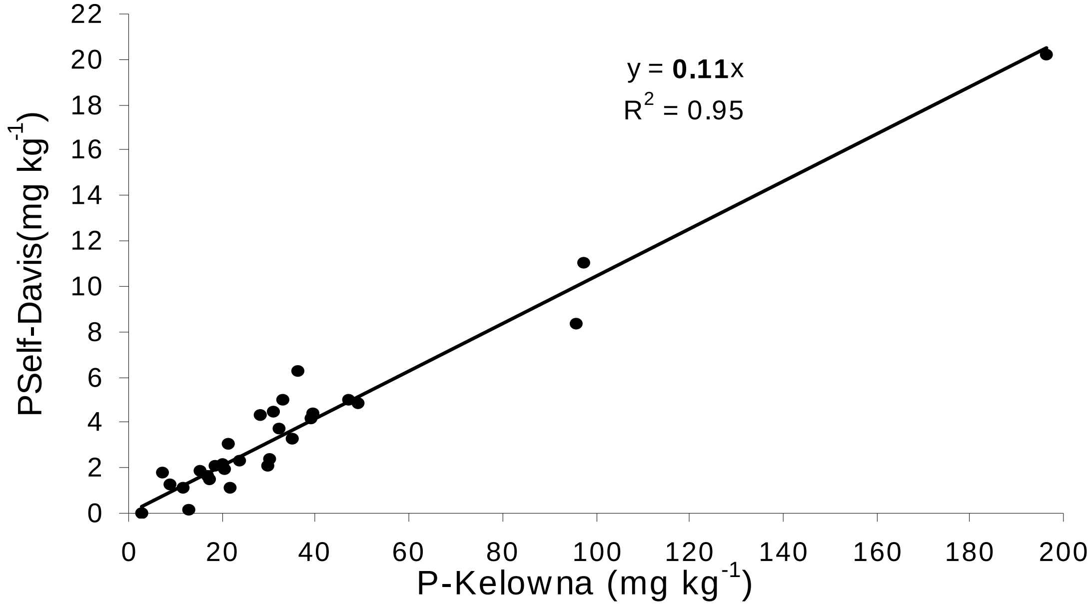

Figure 2.6. General P desorption model for STP KELOWNA

For soils extracted with the KELOWNA P test, the risk is expressed as:

- PDI= $P_{KELOWNA}$*0.11 for G1, G2 and G3

4. $P_{Self\text{-}Davis}$ vs $(P/Al)_{M\text{-}III}$ WEST

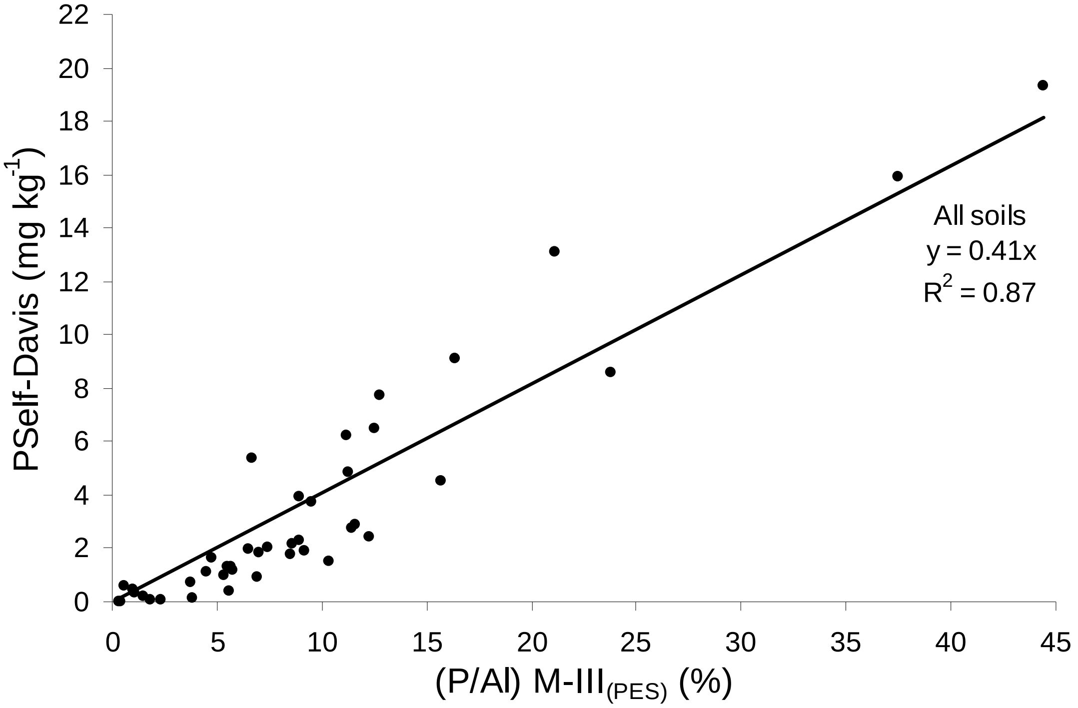

Figure 2.7. General P desorption model for PSI $(P/Al)_{M\text{-}III}$

For Western Canada soils extracted with the M-III test, the risk is expressed as:

- PDI=(P/Al)M-III * 0.41 for G1, G2 and G3

- ***Influence of P_Balance***

Many studies document the long term effects of P application on P accumulation in the soil surface horizon (Tables 2.3a and 2.3b).

Table 2.3a. Models describing STP enrichment in relation to repeated P applications on acidic to neutral soils using STP M-III^{Z} (adapted from Giroux et al., 2002)

Source	Year	Amendement	Location	Initial P level	Average P Balance	Average yearly P variation	Enrichment ratio
				mg P kg^{-1}	kg P ha^{-1}	mg P kg^{-1}	mg P kg^{-1} per 100 kg P Balance ha^{-1}
Bruulsema	2001	Mineral		62.3	-14.6	-2.1	14.7
Cantin	---	Mineral	Quebec	29.8	12.2	0.0	-0.1
Giroux & Lemieux	1996	Mineral	Quebec	47.8	10.0	0.0	0.0
Rivest	1998	Mineral & Manure (Cattle)	Quebec	47.8	8.5	-0.2	-2.1
Tran *et al.*	1996	Manure (Cattle)	Quebec	22.8	40.3	4.3	10.7
Tran *et al.*	1996	Manure (Swine)	Quebec	45.5	29.7	3.4	11.5
Tremblay *et al.*	2002	Mineral	Quebec	60.3	-7.8	-2.2	28.7
Zhang *et al.*	1995	Mineral & Manure (Cattle)	Quebec	50.0	86.2	11.7	13.6
Zhang *et al.*	2006	Mineral	Oklahoma	40.2	6.3	1.0	15.9
Median							11.5

^{z}(M-III: Mehlich-III soil extraction method).

Table 2.3b. Models describing STP enrichment in relation to repeated P applications on calcareous soils using STP OLSEN

Source	Year	Amendement	Location	Initial P level	Average P Balance	Average yearly P Variation	Enrichment ratio
				mg P kg-1	kg P ha-1	mg P kg-1	mg P kg-1 per 100 kg P Balance ha-1
McCartney *et al.*	1998	Mineral	Saskatchewan	13.0	8.9	1.4	15.4
McCartney *et al.*	1998	Mineral	Saskatchewan	8.3	-3.8	0.1	-2.9
Allen & Mallarino	2006	Mineral	Iowa	3.0	22.0	0.7	3.0
Allen & Mallarino	2006	Mineral	Iowa	5.0	24.0	1.4	5.8
Allen & Mallarino	2006	Mineral	Iowa	6.0	22.0	1.7	7.5
Koehler *et al.*	2007	Manure (Swine)	Minnesota	5.0	13.5	1.2	8.9
Heming	2007	Mineral & Manure	UK	22.0	7.0	0.8	10.7
MAFF	2000	Mineral & Manure	UK	n.a.	9.0	0.4	4.2
Shepherd and Whiters	1999	Mineral	UK	41.0	25.0	1.5	5.9
Aulakh *et al.*	2007	Mineral	India	12.0	25.0	0.6	2.2
Tang *et al.*	2008	Mineral	China	4.6	34.0	1.2	3.4
Shen *et al.*	2004	Mineral	China	11.0	-18.9	-0.5	2.7
Shen *et al.*	2004	Mineral	China	11.0	7.6	0.4	4.6
Chang *et al.*	2005	Manure (Cattle)	Alberta	141.0	144.0	16.2	11.3
Chang *et al.*	2005	Manure (Cattle)	Alberta	95.0	259.0	27.9	10.8
Median							5.8

Giroux et al. (2002) reviews different enrichment models from the literature for Quebec (Table 2.3a). Based on the median of these particular models, an enrichment coefficient was used to increase the STP $_{\text{M-III}}$ of a given soil based on the cumulative P_Balance since 1976. A similar review (Table 2.3b) was conducted for calcareous soil using STP $_{\text{OLSEN}}$, from which a median coefficient was derived.

Since fertilization recommendations are being changed according to PSI expressed as $(\text{P/Al})_{\text{M-III}}$, all values will be converted to that unit. Strong correlations exist between STP $_{\text{M-III}}$ (PES)[1] and PSI expressed as $(\text{P/Al})_{\text{M-III}}$ (PES) (Khiari and Sbih, 2005).

Table 2.4. STP $_{\text{M-III}}$ conversion in $(\text{P/Al})_{\text{M-III}}$

Soil group	G1^{z}	G2	G3
MODEL	$(\text{P/Al})_{\text{M-III}}{}^{y} = 0.206 \times \text{STP}_{\text{M-III}}$	$(\text{P/Al})_{\text{M-III}} = 0.171 \times \text{STP}_{\text{M-III}}$	$(\text{P/Al})_{\text{M-III}} = 0.146 \times \text{STP}_{\text{M-III}}$

^{z}G1: Fine-textured group includes: clay loams, silty clay loams, clays, sandy clays, silty clays, and heavy clays; G2: Medium-textured group includes: loams, sandy clay loams, silt loams, and silts; G3: Coarse-textured group includes: sands, loamy sands, and sandy loams).
^{y}M-III: Mehlich-III soil extraction method.

To relate the current level of soil phosphorus to their environmental risk, the P_Source component integrates the risk of water P desorption with the cumulative P_Balance (1981–2006)[2] for each SLC polygon.

The P_Balance on soil can only be calculated every 5 years when the census of agriculture data is available**.** Between the census years, a linear interpolation was used to approximate the P_Balance trends.

$$\text{Cumulative\_PB} = \text{Cumulative\_PB}_{t-1} + \text{PB}_{t-1} + (m_{p1} * t) \qquad (2.6)$$

where:

t represents a 1-year increment;

$\mathbf{m_{p1}}$ represents the slope of PB for the period of reference; m is adjusted $\left(\frac{\Delta PB}{\Delta t}\right)$ for each period (Figure 2.8).

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[1] PES; plasma emission spectrometry/ spectrométrie d'émission au plasma.

[2] The P_Balance methodology is presented in Section 2.2.

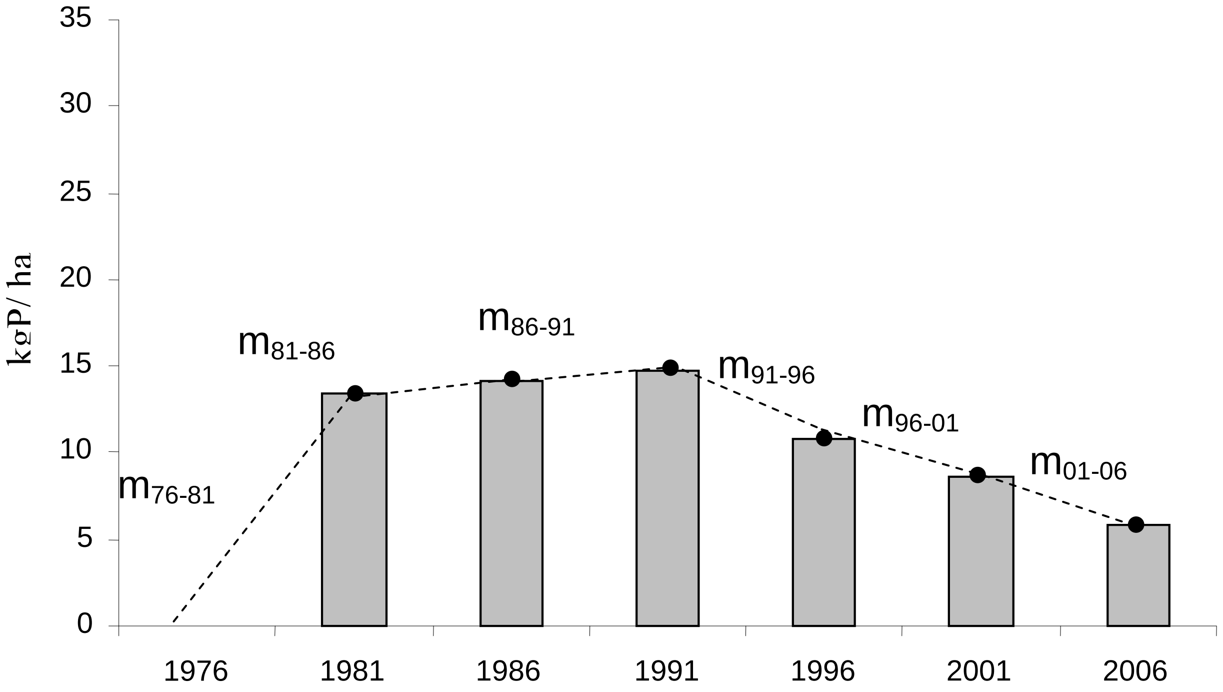

Figure 2.8. Example of P_Balance calculated for a given SLC polygon

After five years, Equation 2.6 can be written as:

$$\text{Cumulative\_PB}_t = \text{Cumulative\_PB}_{t\text{-}1} + (\text{PB}_{t\text{-}1} * 4 + \text{PB}_t{*}4)/2 + \text{PB}_t \tag{2.7}$$

where:

t represents a 5-year period between Census years.

- ***P-Source Algorithm***

P_Source at time *t* can be described using Equation 2.8,

$$P\_Source_t = ([X_0] + PER * Cumulative\_PB) * PDI \tag{2.8}$$

where:

$([X_0] + PER * Cumulative\_PB)$ estimates for $\text{STP}_{\text{OLSEN}}$, $\text{STP}_{\text{KELOWNA}}$ or $(\text{P/Al})_{\text{M-III}}$ (PES) at Census time;

$\boldsymbol{X_0}$ represents the natural level of P predicted from a specific soil test. This value represents the initial P level estimated for 1976 and is taken from Giroux et al. (2008) for estimated for coarse, medium and fine textured soil of Quebec acidic soils. For calcareous soils, a value representing the very low fertility class of different fertility grid (Alberta, Ontario Manitoba) was assumed to be representative of the natural level of soil P;

PER represents the phosphorus enrichment ratio. This ratio is calculated using the median of the enrichment models from the literature (Table 2.3a, 2.3b). **Cumulative_PB** represents the cumulative P_Balance calculated for each Census year. Pedo-transfer coefficients are used to convert the $STP_{M\text{-}III}$ to $(P/Al)_{M\text{-}III}$ (Table 2.4) and the $STP_{M\text{-}III}$ to $STP_{Kelowna}$ (Casson et al., 2006). If the Cumulative_PB is negative, this function is set to zero;

PDI is the linear relationships between $P_{Self\text{-}Davis}$(mg kg^{-1}) and STP_{OLSEN}, $STP_{KELOWNA}$ or $(P/Al)_{M\text{-}III}$ (PES[1]);

For each soil series or soil component of an SLC polygon, increments of the appropriate STP are estimated for 1976, 1981, 1986, 1991, 1996, 2001, and 2006. This STP is then back converted into water extractable $P_{Self\text{-}Davis}$ using the appropriate PDI (Figure 2.4-2.7). Final values for the SLC polygon are then aggregated using the percent coverage of each soil,

$$\text{P\_SOURCE}_{SL} = \frac{(\text{P\_SOURCE}_{CMP1} * \text{PERCENT}_{CMP1}) + (\text{P\_SOURCE}_{CMP2} * \text{PERCENT}_{CMP2}) + \ldots}{\sum PERCENT_{CMP1+CMP2+\ldots}} \quad (2.9)$$

where:

SL represents the SLC polygon number;

CMP represents the component number 1-999;

PERCENT represents the percentage of coverage for the soil component in a polygon.

Limitations and Uncertainties

1. Limits in the SLC database

For P_Source calculations, only the four first components of each SLC polygon were considered. For some regions this represents 100% of the polygon coverage while in the prairies it represents the majority of coverage (>80% coverage for more than 75% of SLC). Using this approach, SLC polygons are compared on the basis of their dominant characteristics considered on a uniform basis.

However, dominant SLC series may not be under agricultural usage. In the same way, the proportion of each soil series in a SLC may not reflect the real proportions of the main soil series under cultivation in a polygon.

2. Limits in the $[X_0]$ parameter

Natural levels of soil phosphorus are dependent of geology and pedogenesis of all soils. Giroux et al (2008) estimated the natural levels of three textural classes. This approach includes the deposition mode of most soil in Quebec (glacial till, fluvio alluvium or marine deposits). For other provinces, this approach may not be valid. No information was found in the literature. The use of a single natural level

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[1] PES, Plasma Emission Spectroscopy

based on the very low agronomic fertility class was done to account of the limitative abundance of phosphorus in the natural environment. This assumption is underestimating natural levels found were apatite is abundant and where alluvium may be accumulating.

3. Limits in the soil P enrichment

P_Balance values are available only for Census years (1976, 1981, 1986, 1991, 1996, 2001, and 2006). To calculate the cumulative P_Balance, we assume a linear trend of P_Balance between two Census years. For years between two Census years, we must rely on regional studies to determine whether the regional P_Balance is being accurately estimated. For SLC polygons that have a very low or very high P_Balance, and for SLC polygons that have a negative cumulative P_Balance, the inclusion of extreme values from the enrichment models in the correction calculations may affect the uncertainty of P_Source estimates. Giroux et al. (2008) demonstrated that very rich soils do not respond the same way to P fertilisation. At high P concentration, stabilisation of the phosphorus added in insoluble forms occurs in a greater proportion than at low P concentration. This phenomenon is called the “retroversion” of phosphorus. Since very little information is know of this phenomenon, it was not included in this version of the P_Source component.

Most P-enrichment models were developed on plots that had been fertilized for many years and are usually site specific. The diversity of STP enrichment equations (Tables 2.3a and 2.3b) probably represent the inherent variability of soil response to their P sorption capacity. By using Equation 2.9 at the SLC polygon scale, we are assuming that the enrichment ratio is similar for all soils. Part of the variability may be attributable to imprecision in the STP measures. For the Mehlich-III test, for example, we estimate the uncertainty to be 7% of the STP value.

4. Limits of the PDI

The model for STP_{OLSEN} and $(P/Al)_{M\text{-}III}$ were performed on a good number of soils samples (n= 268 for STP_{OLSEN} and n= 70 for $(P/Al)_{M\text{-}III}$) and a significant difference was found for the different textural classes shown in the models. However some correlations are not so strong ($R^2 \approx 0.50$) demonstrating the variability of the relationship which is often bound to the recent history of fertilizer application. If more soils of known background had been available for analysis; the regression coefficients may have been more precise.

The model for $STP_{KELOWNA}$, over the soils analysed, could not be calculated for textural classes, as it was done for the P_{OLSEN} and $(P/Al)_{M\text{-}III}$. Although there was a relationship between the model and Fe_{ox}+Al_{ox} concentrations, these elements are usually not determined by routine soil tests in western Canada. A total of 69 out of 82 soils were used to develop the $STP_{KELOWNA}$ model. It is likely that a better general relationship, based on inherent soil characteristics, could be established if more soils with a variety of textures were available for model development.

No models for organic soils were developed at this stage of the project, because most of the organic-soil dominant SLC polygons are missing in the Census data, and which are required for IROWC_P calculations. Because the P_w structure allows the different soil types to be compared, a general model could be developed for cultivated organic soils with an appropriate general STP.

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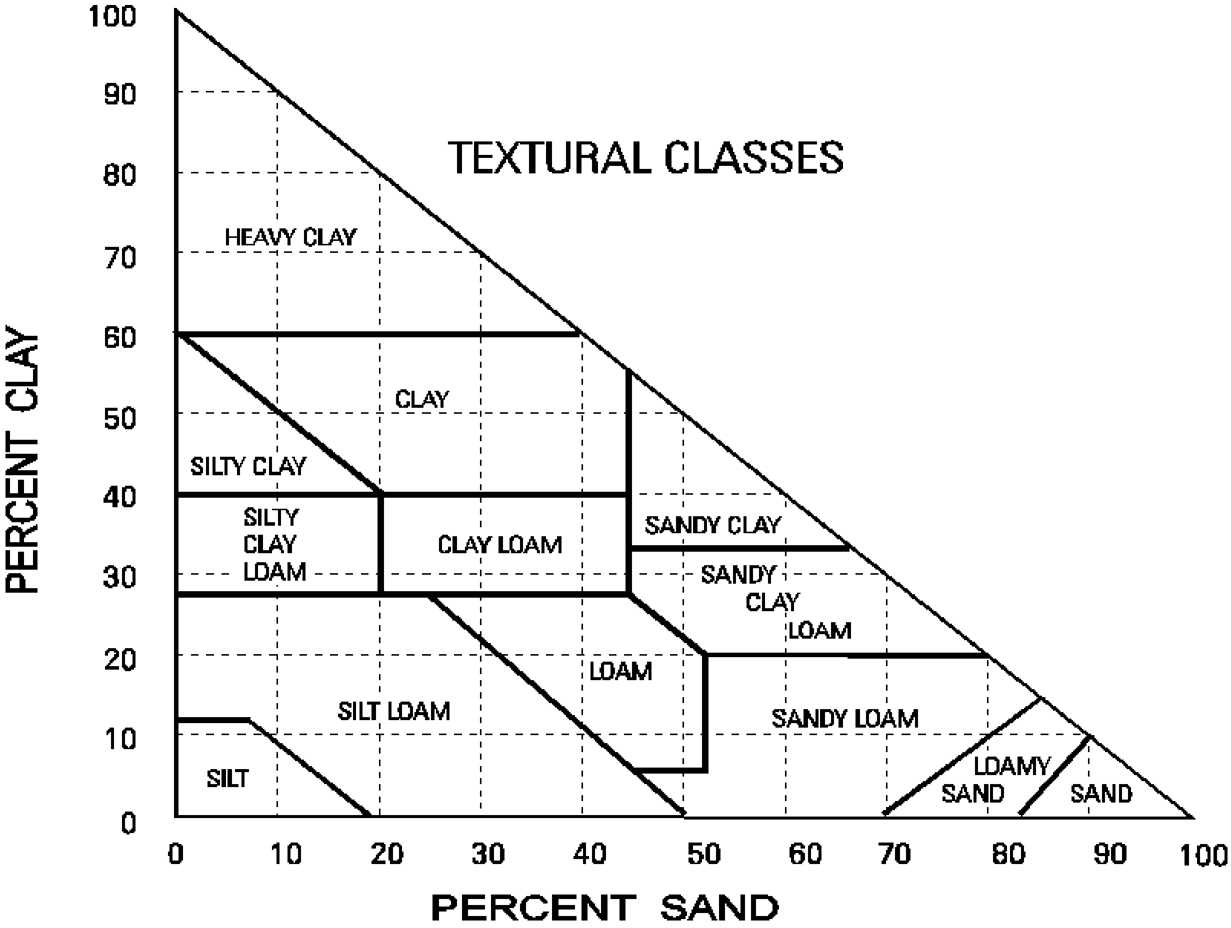
Appendix 1. Soil textural classes triangle



Soil textural classes. Percentages of clay and sand in the main textural classes of soils; the remainder of each class is silt. Source: Soil Classification Working Group. 1998. The Canadian System of Soil Classification. Agric. and Agri-Food Can. Publ. 1646 (Revised). 187 p.

Section 2.1 – P_Balance

Authors

Georges Thériault
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Stéphane Martel

Introduction

The P_Balance subcomponent of the P_Source estimates, as appropriate, the P balance for the agricultural polygons of the Soil Landscapes of Canada (SLC) or the watershed. The reasoning behind the P_Balance is based on two assumptions:

1. Phosphorus comes mainly from two sources: manure from animal herds that are estimated by the P_{manure} subcomponent and phosphated mineral fertilizers applied to crops, which are estimated by the $P_{mineral}$ subcomponent;
2. Phosphorus exports mainly result from P immobilized in crop harvests and are estimated by the $P_{removal}$ subcomponent.

The P_Balance value is expressed as a quantity of P on the basis of the agricultural area of the polygon, i.e., kg P ha^{-1}.

Data Sources

The P_Balance estimates are based on the three subcomponents described above. The source data for these calculations are provided in the following sections of this IROWC_P technical document:

- Section 2.2.1 – P_{manure} pages 29–34
- Section 2.2.2 – $P_{mineral}$ pages 35–54
- Section 2.2.3 – $P_{removal}$ pages 55–58.

Methodology

From the initial assumptions, the calculated P_Balance is based on the following equation:

$$P\_Balance = [P_{manure}] + [P_{mineral}] - [P_{removal}] \qquad (2.10)$$

Limitations and Uncertainties

The limitations of the P_Balance component directly relate to the limitations of the three subcomponents used in the calculation. Briefly, for P_{manure}, the use of standardized manure and P production coefficients, as well as environmental factors and differences in breeding practices, specifically feed (addition of phytase to the ration), introduce a degree of uncertainty that relates to the estimated value of P quantities from manure. For $P_{mineral}$, the estimate of soil P richness, used to estimate applied crop fertilization, is the major source of uncertainty in the $P_{mineral}$ value. Finally, the use of regional (eastern and western Canadian) crop P concentration coefficients and, in some cases, the use of average provincial yields, introduce a degree of uncertainty to the value of $P_{removal}$. For a clearer picture of the limitations and uncertainties associated with P_Balance subcomponents, see the corresponding sections.

Section 2.1.1 – P_{manure}

Authors

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Introduction

The P_{manure} subcomponent estimates the quantity of P from manure produced in the agricultural polygons of the Soil Landscapes of Canada (SLC) or the watershed. The animal categories considered in the P_{manure} calculation are listed in Table 2.5. It is initially assumed that all P from manure produced in an agricultural polygon of the SLC is used to fertilize the crops of the polygon. Transportation of manure between adjacent polygons is not considered because that information is not yet available.

Several studies suggest that the use of phytase (enzyme) in monogastric animals reduces the P content of manure from swine herds by 30% (Grandhi, 2001; Knowlton et al., 2004) and from poultry herds by 25% (Lefrançois and Ouyed, 2004). In Quebec, use of the phytase enzyme in swine production increased from 12% in 1996, to 28% in 1998, 83% in 2001, and 90% in 2003 (BPR Groupe-conseil, 2003; BPR Inc., 2005). Also, for swine production, the percentage use of phytase was 25% in Ontario in 2004 (OMAFRA, 2004) and about 50% in Manitoba in 2006 (Marc Trudelle, Manitoba Conservation, personal communication). For poultry, the percentage use of phytase in Quebec was 3% in 1998 and 54% in 2003 (BPR Inc., 2005). These data form the basis of a second assumption: from 1981 to 1996, Canadian use of phytase for swine and poultry feed was 0%, except for Quebec's swine industry, which reported 12% use in 1996. For 2001, the percentage use of phytase in Ontario's swine industry was similar to other provinces except Quebec and, for 2006, the percentage use was approximately half of Quebec's, according to estimates from Manitoba (Table 2.6). If national data on the sales of phytase enzymes or feeds containing phytase become available, more accurate estimates may be possible.

Data Sources

The P excretion coefficients used by Statistics Canada to estimate P quantities from the American Society of Agricultural Engineers (ASAE, 2003) do not account for the use of phytase in swine and poultry production. Table 2.5 lists the various animal categories considered, along with their average weights and respective manure and P production coefficients. The LVKGP variable (Equation 2.11) of the Census of Agriculture estimates the quantity of P (kg P) from annual manure production for each agricultural polygon of the SLC and incorporates livestock category populations and their respective coefficient based on the following equation:

$$LVKGP = \sum_{i=1}^{n} \left[(animal\_heads)_i * (annual\_P\_excretion\_coefficient)_i \right] \qquad (2.11)$$

where:

i indexes the ***n*** animal categories listed in Table 2.5.

Table 2.5. Animal categories considered in calculating the LVKGP variable from the Census of Agriculture, with respective manure and phosphorus production coefficients

Animal category	Variable from Census of Agriculture (CoA)	Average animal weight (kg)	Manure/1000-kg animal/day (kg)	Manure/ animal/year (kg)	P_{manure}/ 1000-kg animal/day (kg)	P_{manure}/ animal/year (kg)	N_{manure}/ 1000-kg animal/day (kg)	N_{manure}/ animal/ year (kg)
Beef cow	BFCOW	635	58	13444	0.09	21.3	0.34	78.8
Horses	HORSES	450	51	8377	0.07	11.7	0.30	49.3
Wild boar, buffalo, etc.	LVLRG	201	58	4273	0.09	6.8	0.34	25.1
Mink, rabbit, etc.	LVMRF	4	40	59	0.09	0.1	0.42	0.6
Sheep	TSHEEP	45	40	662	0.09	1.4	0.42	7.0
Goat	GOATS	64	41	958	0.11	2.6	0.45	10.5
Bull	BULLS	726	58	15364	0.09	24.4	0.34	90.1
Calf	CALFU1	204	58	4321	0.09	6.9	0.34	25.3
Heifer	HEIFERS	420	58	8904	0.09	14.1	0.34	52.2
Milk cow	MLKCOW	612	102	22706	0.12	26.8	0.55	122.0
Boar	PIGBRS	159	23	1358	0.06	3.3	0.17	9.9
Feeder pig	PIGHOG	61	58	1287	0.15	3.2	0.38	8.5
Piglet	PIGNW	11	148	613	0.35	1.4	0.87	3.5
Sow	PIGSOW	125	30	1358	0.07	3.1	0.21	9.6
Steer	STEERS	454	58	9603	0.09	15.2	0.34	56.3
Broiler/fryer chicken	PLTBRC	0.9	85	28	0.30	0.1	1.10	0.4
Layer hen	PLTLAYH	1.8	64	42	0.30	0.2	0.84	0.6
Pullet	PLTPUL	0.9	85	28	0.30	0.1	1.10	0.4
Turkey	PLTTRKY	6.8	47	117	0.23	0.6	0.62	1.5

Table 2.6. Estimated proportion of swine and poultry herds receiving phytase in their feed

Region	Animal production	Year	Proportion of herd given phytase (%)
Maritime	Swine	≤ 1996	0
		2001	25
		2006	50
	Poultry	≤ 1996	0
		2001	0
		2006	25
Quebec[z]	Swine	≤ 1991	0
		1996	**12**[w]
		2001	**83**
		2006	**90**
	Poultry	≤ 1996	0
		2001	**3**
		2006	**54**
Ontario[y]	Swine	≤ 1996	0
		2001	**25**
		2006	50
	Poultry	≤ 1996	0
		2001	0
		2006	25
Prairies[x]	Swine	≤ 1996	0
		2001	25
		2006	**55**
	Poultry	≤ 1996	0
		2001	0
		2006	25
British Columbia	Swine	≤ 1996	0
		2001	25
		2006	50
	Poultry	≤ 1996	0
		2001	0
		2006	25

[z] BPR Groupe-conseil, 2003; BPR Inc., 2005.

[y] OMAFRA, 2004.

[x] Marc Trudelle, Manitoba Conservation, personal communication.

[w] Values in bold represent numbers from industry reports or personal communications; other values are arbitrary estimates by the authors.

Methodology

In the calculation of P_{manure}, phytase use is considered for only swine and poultry production; manure produced by these animals must be treated separately from other manures.

- ***Calculation steps***

1. Calculate P quantities produced annually by swine and poultry using variables from the Census and their respective P production coefficients from Table 2.5;

$$P_{pig} = \sum_{i=1}^{n} \left[(animal\_heads)_i * (annual\_P\_excretion\_coefficient)_i \right] \tag{2.12}$$

where:

i indexes the ***n*** variables from the census: PIGBRS, PIGHOG, PIGNW, and PIGSOW.

$$P_{poultry} = \sum_{i=1}^{n} \left[(animal\_heads)_i * (annual\_P\_excretion\_coefficient)_i \right] \tag{2.13}$$

where:

i indexes the ***n*** variables from the census: PLTBRC, PLTLAYH, PLTPUL, and PLTTRKY.

2. Calculate the corrected quantities of P produced annually by swine and poultry using variables from the Census and their respective P production coefficients from Table 2.5 and apply the respective correction factors;

$$P_{corrected\_(pig)} = \sum_{i=1}^{n} \left[\begin{array}{l} \left\{ \begin{array}{l} (animal\_heads)_i * (annual - P\_excretion\_coefficient)_i * \\ (\%\_phytase\_feed)_i * (P\_reduction\_coefficient)_i \end{array} \right\} + \\ \left\{ \begin{array}{l} (animal\_heads)_i * (annual - P\_excretion\_coefficient)_i * \\ (1 - (\%\_phytase\_feed)_i) \end{array} \right\} \end{array} \right] \tag{2.14}$$

where:

i indexes the ***n*** variables from the Census: PIGBRS, PIGHOG, PIGNW, and PIGSOW.

$$P_{corrected\_(poultry)} = \sum_{i=1}^{n} \left[\begin{array}{l} \left\{ \begin{array}{l} (animal\_heads)_i * (annual - P\_excretion\_coefficient)_i * \\ (\%\_phytase\_feed)_i * (P\_reduction\_coefficient)_i \end{array} \right\} + \\ \left\{ \begin{array}{l} (animal\_heads)_i * (annual - P\_excretion\_coefficient)_i * \\ (1 - (\%\_phytase\_feed)_i) \end{array} \right\} \end{array} \right] \tag{2.15}$$

where:

i indexes the ***n*** variables from the Census: PLTBRC, PLTLAYH, PLTPUL, and PLTTRKY.

3. Subtract the values determined in Step 1 from the *LVKGP* variable and add the values determined in Step 2 to obtain a corrected value that accounts for the use of phytase, $LVKGP_{phytase}$:

$$LVKGP_{phytase} = \left[\left(LVKGP\right) - \left(P_{(pig)}\right) - \left(P_{(poultry)}\right) + \left(P_{cooected\_(pig)}\right) + \left(P_{corrected\_(poultry)}\right) \right] \qquad (2.16)$$

4. The value $LVKGP_{phytase}$ is reduced on the basis of the agricultural area of the polygon in order to obtain a value for P_{manure} comparable in space and time between polygons and expressed in terms of kg P_{manure} ag ha^{-1}. The sum of the areas of the crops (CROPLND), improved pastures (IMPAST), and unimproved pastures (UNIMPST) of a polygon, taken from the Census of Agriculture, is considered to be the agricultural area of the polygon (Equation 2.17):

$$P_{manure} = \left[\frac{\left(LVKGP_{phytase}\right)}{\sum\left(CROPLND; IMPAST; UNIMPST\right)} \right] \qquad (2.17)$$

Limitations and Uncertainties

P_{manure} is calculated over one year. Estimating the number of heads in each animal category from the Census involves uncertainty, especially for categories with rapid production rotation (e.g., swine and poultry). Using standardized manure and P production coefficients introduces a bias in the quantities of P produced by the herd. Variability in the quantity of P in the manure is a function of environmental factors, such as differences in breeding practices, specifically feed (phytase). Although standardized conversion factors do not consider this variability, it may be generally assumed that the quantity of P_{manure} estimated at the level of the polygon appropriately incorporates intra-polygon variability. More recent data on the use of phytase in animal feed will allow for a more accurate estimate of the quantities of P actually excreted by the animals.

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Section 2.1.2 – $P_{mineral}$

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Introduction

The $P_{mineral}$ subcomponent estimates the quantity of P from phosphated mineral fertilizers used in crop fertilization for the level of the agricultural polygons of the Soil Landscapes of Canada (SLC) or the watershed.

The general initial assumptions are:

- Manures are the first choice for crop fertilization and account for up to 75% of recommended N.
- Potato and vegetable crops are not fertilized with manure.
- Only in Quebec, and only since 2001, have corn grain and corn silage had to follow a fertilization grid based on a P saturation index; therefore, the criterion of 75% of the recommended N is not applicable.
- Only cattle (BFCOW, BULLS, MLKCOW, HEIFERS, STEERS, and CALFU1), sheep (TSHEEP), and goat (GOATS) herds are considered when estimating the fraction of manure that is produced on pasture, and therefore unavailable for crop fertilization (Table 2.5).
- Grass, fruit, nut, and sheltered seed (greenhouse and nursery) crops are not considered when estimating quantities of phosphated mineral fertilizer sold province-wide.

The estimated quantity of $P_{mineral}$ considers the fraction of P_{manure} that receives priority of use to meet crop P demand. The fraction of P_{manure} available for crop fertilization is obtained by subtracting the fraction of P_{manure} found on improved and unimproved pastures from P_{manure}. Only cattle, goat, and sheep herds are considered for pasturing. Manure N and P availability are also considered in crop fertilization estimates. It is assumed that the N contained in the manure fraction that can be used in crop fertilization may contribute as much as 75% of crop N requirement, thereby setting a ceiling for manure use to meet crop fertilization requirements in the $P_{mineral}$ calculation. If surplus quantities of P_{manure} remain after the ceiling for manure use to meet crop requirements is reached, no further treatment is required because the latter has already been accounted for in the P_{manure} component.

The amount of P recommended for field crops is based on average soil P content, while for vegetable production, the average recommendation was used as a reference. Depending on the type of vegetable, fertilizer recommendations vary widely and the land areas reported in the Census of Agriculture include all types of vegetables. To better represent the relative proportions of the principal types of vegetables grown in each province, Statistics Canada (CANSIM) data can be used to calculate average recommendations for each province. These recommendations vary across Census years according to the changes in vegetable growing areas.

Data Sources

Crop categories considered in the $P_{mineral}$ calculation are listed in Table 2.7. The initial data used to calculate $P_{mineral}$ for each agricultural polygon of the SLC are presented in Tables 2.8 through 2.13. Two of the six master files presented in Table 2.8 refer to groups of secondary files (Tables 2.9 and 2.10) and two of the secondary files from Table 2.10 refer to a group of reference files (Tables 2.11 to 2.13).

Fertilizer recommendations are taken from fertilization guides for New Brunswick, Quebec, Ontario, Manitoba, and British Columbia. For field crops in the Maritime Provinces and British Columbia, the recommendations are from fertilization grids for New Brunswick and Manitoba, respectively. The recommendations concerning all vegetable crops within Canada are taken from Quebec's fertilization grids. Manitoba's recommendations were used as a reference for the three Prairie Provinces.

Table 2.7. Vegetable crops considered in calculating the $P_{mineral}$ subcomponent and respective Census variables

Crop categories	Variables
Corn grain	CORNGR
Corn silage	CORNSLG
Soybeans	SOYBNS
Winter cereals (fall rye and winter wheat)	WHTRYE
Spring wheat	WHTSPG
Mixed grains (oats, barley, spring rye, and mixed grains)	GRNCRL
Alfalfa and alfalfa mixtures	ALFALFA
Tame hay and other forage crops (total)	OHAYFD
Potatoes	POTATS
Vegetables ($P_{mineral}$ only)	TOTVEG

Table 2.8. Master files for calculating P quantities of mineral origin

Master files	Unit	Source
Crop areas	ha	Census of Agriculture
Recommended P	kg P	Provincial fertilization guides
Recommended N	kg N	Provincial fertilization guides
Relative soil P content	Category	Table 2.9
P and N from manure available for crop fertilization	kg P-N yr^{-1}	Table 2.10
Phosphated fertilizers sold in the province (adjusted value)	kg P	Korol (2002); CFI-Retail Sales Stats Report (2007)

Table 2.9. Secondary files for calculating relative soil P content

Secondary files (relative soil P content)	Unit	Source
Crop and pasture area	ha	Census of Agriculture
Total P from manure	kg P yr^{-1}	Census of Agriculture
Crop P uptake (P uptake files)	kg P yr^{-1}	IROWC_P files

Table 2.10. Secondary files for calculating P and N quantities from manure available for crop fertilization

Secondary files (P and N availability)	Unit	Source
P and N quantities deposited on pasture	kg P and N yr^{-1}	Table 2.11
Reference file for N and P availability		Tables 2.12 and 2.13
Number of animals	head	Census of Agriculture
Average manure production by animal category	kg manure	Statistics Canada and AAFC
P and N production coefficients by animal category	kg P-N $head^{-1}$	Statistics Canada and AAFC

Table 2.11. Reference files for calculating P and N quantities deposited on pasture

Reference files (animal and manure management)	Unit	Source
Number of animals suitable for pasturing (cattle and sheep herd)	head	Census of Agriculture
Number of animals (cattle and sheep herd) on improved and unimproved pasture	head	Statistics Canada-FEMS (2006)
Approximate time on improved and unimproved pasture	day	Statistics Canada-FEMS (2006)
Areas on improved and unimproved pasture	ha	Census of Agriculture
Total P and N from manure	kg P-N yr^{-1}	Census of Agriculture
Average manure production by animal category	kg manure	Statistics Canada and AAFC
P and N production coefficients by animal category	kg P-N $head^{-1}$	Statistics Canada and AAFC

Table 2.12. Reference files for calculating P availability

Reference files (phosphorus)	Source
Soil texture	CanSIS
Liquid/solid ratio (available since 1996)	Census of Agriculture
Spreading period ratio (summer, fall, winter, and spring)	Statistics Canada-FEMS (2001, 2006)
Spreading method ratio (incorporation delay: <24 h, 1–7 days, >7 days)	Statistics Canada-FEMS (2001, 2006)
P availability coefficient (manure type and soil texture)	CRAAQ (2003)
Division factor (spreading period)	CRAAQ (2003)

Table 2.13. Reference files for calculating N availability

Reference files (nitrogen)	Source
Soil texture	CanSIS
Liquid/solid ratio (available since 1996)	Census of Agriculture
Crop type ratio (pasture and other)	Census of Agriculture
Spreading period ratio (summer, fall, winter, and spring)	Statistics Canada-FEMS (2001, 2006)
Spreading method ratio (incorporation delay: <24 h, 1–7 days, >7 days)	Statistics Canada-FEMS (2001, 2006)
N availability coefficient (manure type and soil texture)	CRAAQ (2003)
Division factor (spreading method, manure type, and incorporation delay)	CRAAQ (2003)
Division factor (spreading period, soil texture, crop type, and manure type)	CRAAQ (2003)

Methodology

- ***Calculation steps***

1. Calculate the fraction of P_{manure} available for crop fertilization;

– Determine the annual quantity of P_{manure} produced by herds considered suitable for pasturing (cattle, sheep, and goats):

$$\left(Annual\_P_{manure}\right)_i = \left[\left(animal\_heads\right)_i * \left(annual\_P\_excretion\_coefficient\right)_i\right] \tag{2.18}$$

where:

i indexes the ***n*** categories of animals suitable for pasturing (cattle, sheep, and goats).

– Determine portion of herds (cattle, sheep, and goats) on pasture:

$$\left(animal\_ratio_i\right)_{pasture} = \left[\frac{\left(Nb\_animal_i\right)_{pasture}}{\left(Nb\_animal_i\right)_{permanently\_outside} + \left(Nb\_animal_i\right)_{buildings}}\right] \tag{2.19}$$

where:

i indexes the animal categories suitable for pasturing (cattle, sheep, and goats);

$\boldsymbol{(Nb\_animal)_{pasture}}$, $\boldsymbol{(Nb\_animal)_{permanently\_outside}}$, and $\boldsymbol{(Nb\_animal)_{buildings}}$ are given by Questions 36, 5, and 8, respectively of FEMS_2006.

– Determine the fractions of P_{manure} produced on pasture by cattle, sheep, and goat herds:

$$\left(P_{manure\_pasture}\right)_i = \left[\begin{array}{l} \left\{\left(Annual\_P_{manure}\right)_i * \left(animal\_ratio_i\right)_{pasture}\right\} * \\ \left\{\begin{array}{l} \left\langle\left(\dfrac{days_{impast}}{365}\right) * \left(\dfrac{area_{impast}}{area_{impast} + area_{unimpst}}\right)\right\rangle + \\ \left\langle\left(\dfrac{days_{unimpst}}{365}\right) * \left(\dfrac{area_{unimpst}}{area_{impast} + area_{unimpst}}\right)\right\rangle \end{array}\right\} \end{array}\right] \quad (2.20)$$

where:

i indexes the ***n*** categories of animals (cattle, sheep, and goats);

days$_{impast}$ and ***days$_{unimpst}$*** are given by Question 39 of FEMS_2006;

area$_{impast}$ and ***area$_{unimpst}$*** are given by the Census of Agriculture.

– Determine the fractions of P_{manure} available for crop fertilization from cattle, sheep, goat, poultry, and other herds:

The quantity of P_{manure} available for crop fertilization from the cattle herd is estimated by subtracting the quantity produced on pasture from the total quantity produced

$$\left(P_{manure\_fertilizer}\right)_{bovine} = \left[\left(Annual\_P_{manure}\right)_{bovine} - \left(P_{manure\_pasture}\right)_{bovine}\right] \quad (2.21)$$

The quantity of P_{manure} available for crop fertilization from the swine herd is given by Equation 2.14 and the quantity from the poultry herd is given by Equation 2.15.
The quantity of P_{manure} available for crop fertilization from other animal categories ($(P_{manure\_fertilizer})_{Other}$, which includes all animals except cattle, swine, and poultry herds, is estimated by subtracting the quantity of P_{manure} produced on pasture and the quantities of P_{manure} produced by cattle, swine, and poultry from the total quantity of P_{manure} produced.

$$\left(P_{manure\_fertilizer}\right)_{other} = \left[LVKGP_{phytase}\right] - \left[\begin{array}{l} \left\{\sum_{i=1}^{n}\left(P_{manure\_pasture}\right)_i\right\} + \\ \left\{\left(P_{manure\_fertilizer}\right)_{bovine} + \left(P_{corrected\_(pig)}\right) + \left(P_{corrected\_(poultry)}\right)\right\} \end{array}\right] \quad (2.22)$$

where:

i indexes the ***n*** categories of animals suitable for pasturing (cattle, sheep, and goat).

– Determine the corrected fractions of P_{manure} available to estimate the total quantity of P available for crop fertilization:

The fractions of P_{manure} available for crop fertilization must be corrected to account for crop P availability. The P availability coefficients consider manure state (solid or liquid; Table 2.14) and spreading period (spring-summer or fall-winter; Table 2.15) and are taken from the Guide de Référence en Fertilisation (CRAAQ, 2003).

Table 2.14. Phosphorus availability coefficients as a function of manure state (solid or liquid)

Animal category	Manure state	P availability coefficient
Cattle and poultry	solid	0.65
Cattle, poultry, and swine	liquid	0.80

The liquid and solid manure ratio calculations are based on four variables from the Census of Agriculture (MIRRIG, MLIQINJ, MLIQSUR, and MSOLID). The first three variables represent the liquid portion and the fourth, the solid portion. Thus,

$$Liquid\_ratio = \left[\frac{(MIRRIG + MLIQINJ + MLIQSUR)}{(MIRRIG + MLIQINJ + MLIQSUR + MSOLID)}\right] \tag{2.23}$$

and

$$Solid\_ratio = \left[\frac{(MSOLID)}{(MIRRIG + MLIQINJ + MLIQSUR + MSOLID)}\right] \tag{2.24}$$

For the cattle herd,

$$\left(Corr1\_P_{manure\_fertilizer}\right)_{bovine} = \left[\left\{\left(P_{manure\_fertilizer}\right)_{bovine}\right\}\right] * \begin{bmatrix}\left\{(Liquid\_ratio) * (availability\_coeff)_{liquid}\right\} + \\ \left\{(Solid\_ratio) * (availability\_coeff)_{solid}\right\}\end{bmatrix} \tag{2.25}$$

For the swine herd (100% of the manure is considered as being in liquid form),

$$\left(Corr1\_P_{manure\_fertilizer}\right)_{pig} = \left[P_{corrected\_(pig)}\right] * \left[(availability\_coeff)_{liquid}\right] \tag{2.26}$$

For the poultry herd,

$$\left(Corr1\_P_{manure\_fertilizer}\right)_{poultry} = \left[P_{corrected\_(poultry)}\right] * \begin{bmatrix}\left\{(Liquid\_ratio) * (availability\_coeff)_{liquid}\right\} + \\ \left\{(Solid\_ratio) * (availability\_coeff)_{solid}\right\}\end{bmatrix} \tag{2.27}$$

For the other herd,

$$\left(Corr1\_P_{manure\_fertilizer}\right)_{other} = \left[\left(P_{manure\_fertilizer}\right)_{other}\right] * \begin{bmatrix}\left\{(Liquid\_ratio) * (availability\_coeff)_{liquid}\right\} + \\ \left\{(Solid\_ratio) * (availability\_coeff)_{solid}\right\}\end{bmatrix} \tag{2.28}$$

The total quantity of $P_{manure\_fertilizer}$ corrected for the manure state is estimated by summing the four components:

$$\left(Corr1\_P_{manure\_fertilizer}\right)_{total} = \sum_{i}\left[\left(Corr1\_P_{manure\_fertilizer}\right)_{i}\right] \tag{2.29}$$

where:

i indexes the cattle, swine, poultry, and other categories.

To estimate the total quantity of P from manure available for crop fertilization, a second correction is made to account for the spreading period (spring-summer and fall-winter).

Table 2.15. Phosphorus availability coefficients as a function of spreading period

Spreading period	P loss coefficients
Spring-summer	1.0
Fall-winter	1.6

$$P_{manure\_fertilizer} = \left[\left(Corr1\_P_{manure\_fertilizer}\right)_{total}\right] * \left[\begin{array}{l}\left\{\dfrac{(\%\_spread)_{spring\_summer}}{(P\_loss\_factor)_{spring\_summer}}\right\} + \\ \left\{\dfrac{(\%\_spread)_{fall\_winter}}{(P\_loss\_factor)_{fall\_winter}}\right\}\end{array}\right] \tag{2.30}$$

where:

$(\%\_spread)_{spring\_summer}$ and $(\%\_spread)_{fall\_winter}$ are given by the LFAS survey.

2. Calculate the fraction of N_{manure} available for crop fertilization;

Since, in several cases, the fraction of available N contained in the manure spread over the crops determines the quantity of manure for application, this fraction ($N_{manure\_fertilizer}$) must be estimated. The procedure for estimating the $N_{manure\_fertilizer}$ fraction follows essentially the same reasoning as that for estimating the $P_{manure\_fertilizer}$ fraction. The N_{manure} value is corrected by accounting for manure-spreading method and period (FEMS_2006), manure incorporation delay (FEMS_2006), manure type – solid or liquid (Census_2006), crop type (Census_2006), and soil texture (CanSIS).

– Determine the quantity of N_{manure} produced annually by herds considered suitable for pasturing (cattle, sheep, and goat):

$$\left(Annual\_N_{manure}\right)_{i} = \left[\left(animal\_heads\right)_{i}\right] * \left[\left(annual\_N\_excretion\_coefficient\right)_{i}\right] \tag{2.31}$$

where:

i indexes the animal categories suitable for pasturing (cattle, sheep, and goat).

– Determine the portion of herds (cattle, sheep, and goat) on pasture:

$$\left(animal\_ratio_i\right)_{pasture} = \left[\frac{\left(Nb\_animal_i\right)_{pasture}}{\left\{\left(Nb\_animal_i\right)_{permanently\_outside} + \left(Nb\_animal_i\right)_{buildings}\right\}}\right] \tag{2.32}$$

where:

i indexes the animal categories suitable for pasturing (cattle, sheep, or goat);

(*Nb_animal*)*pasture*, **(*Nb_animal*)*permanently_outside*** and **(*Nb_animal*)*buildings*** are given respectively by Questions 36, 5, and 8 of FEMS_2006.

– Determine the fractions of N_{manure} produced on pasture by cattle, sheep, and goat herds:

$$\left(N_{manure\_pasture}\right)_i = \left[\begin{array}{l}\left(Annual\_N_{manure}\right)_i \\ *\left(animal\_ratio_i\right)_{pasture}\end{array}\right] * \left[\begin{array}{l}\left\{\left(\frac{(days)_{impast}}{365}\right) * \left(\frac{area_{impast}}{area_{impast} + area_{unimpst}}\right)\right\} + \\ \left\{\left(\frac{(days)_{unimpst}}{365}\right) * \left(\frac{area_{unimpst}}{area_{impast} + area_{unimpst}}\right)\right\}\end{array}\right] \tag{2.33}$$

where:

i indexes the animal categories (cattle, sheep, or goat);

days

$$\left(N_{manure\_fertilizer}\right)_{pig} = \sum_{i=1}^{n}\left[\left(animal\_heads\right)_i * \left(annual\_N\_excretion\_coefficient\right)_i\right] \qquad (2.35)$$

where:

i indexes the ***n*** variables from the Census (Table 2.5): PIGBRS, PIGHOG, PIGNW, and PIGSOW.

The quantity of $N_{manure\_fertilizer}$ from the poultry herd available for crop fertilization is equal to the quantity of N produced annually:

$$\left(N_{manure\_fertilizer}\right)_{poultry} = \sum_{i=1}^{n}\left[\left(animal\_heads\right)_i * \left(annual\_N\_excretion\_coefficient\right)_i\right] \qquad (2.36)$$

where:

i indexes the ***n*** variables from the Census (Table 2.5): PLTBRC, PLTLAYH, PLTPUL, and PLTTRKY.

The quantity of N_{manure} available for crop fertilization from the other herd, which includes all animals except cattle, swine, and poultry, is estimated by subtracting the quantity of N_{manure} produced on pasture and the quantities of N_{manure} produced by cattle, swine, and poultry from the total quantity of N_{manure} produced:

$$\left(N_{manure\_fertilizer}\right)_{other} = \left[LVKGN\right] - \left[\begin{array}{l} \left\{\sum_{i=1}^{n}\left(N_{manure\_pasture}\right)_i\right\} + \\ \left\{\left(N_{manure\_fertilizer}\right)_{bovine} + \left(N_{manure\_fertilizer}\right)_{pig} + \left(N_{manure\_fertilizer}\right)_{poultry}\right\} \end{array}\right] \qquad (2.37)$$

where:

i indexes the ***n*** categories of animals suitable for pasturing (cattle, sheep, and goats).

– Determine the corrected fractions of N_{manure} available to estimate the total quantity of N available for crop fertilization:

The fractions of N_{manure} available for crop fertilization must be corrected to account for crop N availability. The N availability coefficients consider animal category, manure state (solid or liquid), and the texture of the soil over which the manure is spread (Table 2.16). An initial series of N loss (volatilization) coefficients is a function of spreading method, incorporation delay, and animal category (Table 2.17). A second series of N loss (volatilization) coefficients is a function of spreading period, crop category, and soil texture group (Table 2.18). The coefficients used are taken from the Guide de Référence en Fertilisation (CRAAQ, 2003).

Table 2.16. Nitrogen availability coefficients as a function of animal category, manure type (solid or liquid) spread, and soil texture

Animal category	Manure type	Soil texture^z	
		S, LS, SL	Other
Bovine	solid	0.55	0.45
	liquid	0.60	0.50
Swine	liquid	0.70	0.60
Poultry	solid	0.75	0.65
	liquid	0.85	0.75

^{z}S=Sand, LS=loamy sand, and SL=sandy loam.

Table 2.17. Loss coefficients (Loss_factor1) as a function of manure type (liquid or solid), spreading method (injection, sprinkler, irrigation, or spreader), incorporation delay (<24 h or >24 h), and animal category

Spreading method	Incorporation delay	Manure type				
		swine	bovine		poultry	
		liquid	liquid	solid	liquid	solid
Surface injection		1.0	1.0		1.0	
Irrigation	<24 h	1.2	1.2		1.3	
	>24 h	1.4	1.4		1.5	
Sprinkler	<24 h	1.1	1.1		1.2	
	>24 h	1.3	1.3		1.4	
Spreader	<24 h			1.1		1.3
	>24 h			1.3		1.5

Table 2.18. Nitrogen loss coefficients (*Loss_factor2*) as a function of manure type (liquid or solid), spreading period, crop type (pasture or other), and soil texture group

Manure type	Crop category	Pasture		Other	
	Soil texture^z	S, LS, SL	Other	S, LS, SL	Other
Liquid	spring-summer	1.1	1.0	1.1	1.0
	fall-winter	1.6	1.4	1.8	1.4
Solid	spring-summer	1.0	1.0	1.0	1.0
	fall-winter	1.3	1.2	1.4	1.3

^{Z}S=sand, LS=loamy sand, SL=sandy loam or other.

Liquid and solid manure ratios are calculated from Equations (2.23) and (2.24). Since the N availability coefficient is a function of soil texture group, an initial correction is made to estimate N availability for the first three soil components per SLC polygon (CMP1, CMP2, and CMP3).

For the cattle herd,

$$\left(Corr1\_N_{manure\_fertilizer}\right)_{bovine} = \sum_{ij} \left| \begin{matrix} \left[\left(N_{manure\_fertilizer}\right)_{bovine} * \left(\%\_texture_j\right)_i\right] * \\ \left[\begin{matrix} \left\{\left(liquid\_ratio\right) * \left(availability\_coeff_j\right)_{liquid}\right\} + \\ \left\{\left(solid\_ratio\right) * \left(availability\_coeff_j\right)_{solid}\right\} \end{matrix} \right] \end{matrix} \right| \tag{2.38}$$

where:

i indexes the three CMP components of the polygon and ***j*** indexes the texture groups (S, LS, SL, and other).

For the swine herd (100% of the manure is considered to be in liquid form),

$$\left(Corr1\_N_{manure\_fertilizer}\right)_{pig} = \sum_{ij} \left[\begin{matrix} \left(N_{manure\_fertilizer}\right)_{pig} * \left(\%\_texture_j\right)_i * \\ \left(availability\_coeff_j\right)_{liquid} \end{matrix} \right] \tag{2.39}$$

where:

i indexes the three CMP components of the polygon and ***j*** indexes the texture groups (S, LS, SL, and other).

For the poultry herd,

$$\left(Corr1\_N_{manure\_fertilizer}\right)_{poultry} = \sum_{ij} \left| \begin{matrix} \left[\left(N_{manure\_fertilizer}\right)_{poultry} * \left(\%\_texture_j\right)_i\right] * \\ \left[\begin{matrix} \left\{\left(liquid\_ratio\right) * \left(availability\_coeff_j\right)_{liquid}\right\} + \\ \left\{\left(solid\_ratio\right) * \left(availability\_coeff_j\right)_{solid}\right\} \end{matrix} \right] \end{matrix} \right| \tag{2.40}$$

where:

i indexes the three CMP components of the polygon and ***j*** indexes the texture groups (S, LS, SL, and other).

For the other herd,

$$\left(Corr1\_N_{manure\_fertilizer}\right)_{other} = \sum_{ij} \left| \begin{matrix} \left[\left(N_{manure\_fertilizer}\right)_{other} * \left(\%\_texture_j\right)_i\right] * \\ \left[\begin{matrix} \left\{\left(liquid\_ratio\right) * \left(avg\_availability\_coeff_j\right)_{liquid}\right\} + \\ \left\{\left(solid\_ratio\right) * \left(avg\_availability\_coeff_j\right)_{solid}\right\} \end{matrix} \right] \end{matrix} \right| \tag{2.41}$$

where:

$$\left(avg\_availability\_coeff_j\right)_{liquid} = \left[\frac{\sum_j \left(availability\_coeff_j\right)_{liquid}}{3}\right] \tag{2.42}$$

and

$$\left(avg\_availability\_coeff_j\right)_{solid} = \left[\frac{\sum_j \left(availability\_coeff_j\right)_{solid}}{2}\right] \tag{2.43}$$

where:

i indexes the three CMP components of the polygon and ***j*** indexes the texture groups (S, LS, SL, and other).

A second correction to account for volatilization losses considers manure type (liquid or solid), spreading method (variable from the Census of Agriculture) (MLIQINJ, MLIQSUR, MIRRIG, and MSOLID), incorporation delay (<24 h or >24 h), and animal category, using loss_factor1 (Table 2.17).

For the cattle, swine, and poultry herds,

$$\left(Corr2\_N_{manure\_fertilizer}\right)_i = \sum_j \left[\begin{array}{l} \left\{\left(Corr1\_N_{manure\_fertilizer}\right)_i * \left(\%\_spreading\_method\right)_j\right\} * \\ \left\{\left(\frac{\left(\%\_<24h\right)}{\left(loss\_factor1\right)_{j_{(<24h)}}}\right) + \left(\frac{\left(\%\_>24h\right)}{\left(loss\_factor1\right)_{j_{(>24h)}}}\right)\right\} \end{array}\right] \tag{2.44}$$

where:

i indexes one of the three herds (cattle, swine, or poultry) and ***j*** indexes one of the four spreading methods (injection – MLIQINJ, liquid surface – MLIQSUR, irrigation – MIRRIG, and solid surface – MSOLID).

For the other herd, the loss coefficients used (avg_loss_factor1) are an average of the loss coefficients. Thus,

$$\left(Corr2\_N_{manure\_fertilizer}\right)_{other} = \sum_j \left[\begin{array}{l} \left\{\left(Corr1\_N_{manure\_fertilizer}\right)_{other} * \left(\%\_spreading\_method\right)_j\right\} * \\ \left\{\left(\frac{\left(\%\_<24h\right)}{\left(avg\_loss\_factor1\right)_{j_{(<24h)}}}\right) + \left(\frac{\left(\%\_>24h\right)}{\left(avg\_loss\_factor1\right)_{j_{(>24h)}}}\right)\right\} \end{array}\right] \tag{2.45}$$

where:

$$(avg\_loss\_factor1)_{jk} = \left[\frac{\sum_{j} (loss\_factor1)_{jk}}{(number\_of\_loss\_factor1)_{jk}} \right] \tag{2.46}$$

where:

j represents one of the four spreading methods (injection – MLIQINJ, liquid surface – MLIQSUR, irrigation – MIRRIG, and solid surface – MSOLID);

k represents one of the two incorporation delays (<24 h or >24 h).

To estimate the total quantity of N from the manure and available for crop fertilization, a third and final correction is made. This correction estimates losses through volatilization, accounting for the soil texture group (S, LS, SL, and other) in each of the first three components (CMP1, CMP2, and CMP3) of the polygon's soil, crop type (pasture or other), manure type (liquid or solid), and spreading period (spring-summer or fall-winter) using loss_factor2 (Table 2.18). Thus,

$$N_{manure\_fertilizer} = \sum_{ijkmn} \left\{ \begin{array}{l} (Corr2\_N_{manure\_fertilizer})_i * (\%\_texture_k)_j * (\%\_manure\_type)_m * \\ (\%\_spread)_n * \left[\dfrac{\%\_pasture}{(loss\_factor2)_{kmn-pasture}} + \dfrac{\%\_other}{(loss\_factor2)_{kmn-other}} \right] \end{array} \right\} \tag{2.47}$$

where:

i indexes the animal herds;

j, the first three components of the polygon's soil;

k, the two texture groups (S-LS-SL and other);

m, the two manure types;

n, the two spreading periods.

3. Calculate crop P and N fertilization recommendations and the corrected crop mineral P fertilization recommendation;

Phosphorus fertilization recommendations are usually based on a soil analysis that estimates soil P richness. By classifying the polygons according to soil P relative richness, the recommended P doses may be varied. From a historical perspective, we can assume that soil P enrichment is related to P quantities added through the regular use of manure as a fertilizer source or to a P surplus from manure, as compared with P quantities exported via crop uptake. Therefore, the soil P relative richness index is calculated as follows:

$$SoilP\_relative\_richness\_index = \left[\frac{\left(P_{manure\_fertilizer}\right) - \left(P_{removal}\right)}{\left(CRPLND + IMPAST + UNIMPST\right)} \right] \tag{2.48}$$

Polygons are categorized for P richness based on the value of the P relative richness index. The number of richness categories is a function of the number of P index classes (Soil Test Phosphorus and P Index) in provincial reference fertilization grids (Table 2.19). When the P relative richness index gives a value equal to or less than 0, the polygon is categorized as having a P richness of 1. More than 99% of the polygons having a P relative richness greater than 0 give values of less than 100. Thus, the highest P richness category also includes polygons having a P relative richness index greater than 100 and the intermediate P richness categories give P relative richness index values ranging between 0 and 100 (Table 2.20).

Table 2.19. Number of P index classes in effect in the fertilization grids and number of P relative richness categories by province

Province	Number of P index classes		Number of P richness categories	Notes
	Crops	Vegetables		
British Columbia	10	5	5	• Crop and vegetable P index classes from Manitoba fertilization grids. • Some crop P index classes are paired to obtain five P richness categories.
Alberta	10	5	5	• Crop and vegetable P index classes from Manitoba fertilization grids. • Some crop P index classes are paired to obtain five P richness categories.
Saskatchewan	10	5	5	• Crop and vegetable P index classes from Manitoba fertilization grids. • Some crop P index classes are paired to obtain five P richness categories.
Manitoba	10	5	5	• Some crop P index classes are paired to obtain five P richness categories.
Ontario	13	13	6	• Some crop P index classes are paired to obtain six P richness categories.
Quebec	7	7	7	• Some crop P index classes are paired to obtain seven P richness categories.
New Brunswick	6	7	6	• Vegetable P index classes from Quebec fertilization grids. • Some vegetable P index classes are paired to obtain six P richness categories.
Nova Scotia	6	7	6	• Crop P index classes from New Brunswick fertilization grids. • Vegetable P index classes from Quebec fertilization grids. • Some vegetable P index classes are paired to obtain six P richness categories.
Prince Edward Island	6	7	6	• Crop P index classes from New Brunswick fertilization grids. • Vegetable P index classes from Quebec fertilization grids. • Some vegetable P index classes are paired to obtain six P richness categories.
Newfoundland	6	7	6	• Crop P index classes from New Brunswick fertilization grids. • Vegetable P index classes from Quebec fertilization grids. • Some vegetable P index classes are paired to obtain six P richness categories.

Table 2.20. Phosphorus richness categories and corresponding phosphorus richness index values

Number of P richness categories	P richness category	P relative richness index values, Equation (2.48)
5	1	index ≤ 0
	2	0 < index < 25
	3	25 ≤ index <50
	4	50 ≤ index <75
	5	index ≥ 75
6	1	index ≤ 0
	2	0 < index < 20
	3	20 ≤ index <40
	4	40 ≤ index <60
	5	60 ≤ index <80
	6	index ≥ 80
7	1	index ≤ 0
	2	0 < index < 16.6
	3	16.6 ≤ index <33.2
	4	33.2 ≤ index <49.8
	5	49.8 ≤ index <66.4
	6	66.4 ≤ index ≥ 83
	7	index ≥ 83

For each SLC polygon of a province, the total quantity of P necessary to satisfy the crop P fertilizer recommendation is calculated by multiplying the crop areas by their P recommendations corresponding to the P relative richness index, obtained from Equation (2.48), classified according to the number of P richness categories for the province (Table 2.19):

$$P_{recpoly} = \sum_{i=1}^{n} \left[(Area) * (P\_recommendation) \right]_i \tag{2.49}$$

where:

i indexes the different crops.

For each polygon of a province, the total quantity of N required to satisfy the crop N fertilization recommendations is calculated by multiplying the crop areas by their N recommendations from that province's fertilization grids:

$$N_{recpoly} = \sum_{i=1}^{n} \left[(Area) * (N\_recommendation) \right]_i \tag{2.50}$$

where:

i indexes the different crops.

The mineral P fertilization recommendation must be corrected to account for the quantity of $P_{manure\_fertilizer}$ available for crop fertilization. The quantity of $P_{manure\_fertilizer}$ available for crop fertilization considers the assumption that a maximum of 75% of the crop N requirements can be satisfied by manure. Thus, when $(0.75N_{recpoly})$ is less than $(N_{manure})_{fertilizer}$, a correction factor for $(P_{manure})_{fertilizer}$ corresponding to the quantity of manure not used in crop fertilization is estimated by Equation (2.51) to adjust $(P_{manure})_{fertilizer}$; otherwise, no adjustment is necessary:

$$Factor\_(P_{manure})_{fertilizer} = \left[(N_{manure})_{fertilizer} - (0.75N_{recpoly})\right] * \left[\frac{(P_{manure})_{polygon}}{(N_{manure})_{polygon}}\right] \tag{2.51}$$

The adjusted quantity of $P_{manure\_fertilizer}$ is calculated by subtracting the quantity of manure not used in crop fertilization from the total quantity of $P_{manure\_fertilizer}$.

$$adjusted\_(P_{manure})_{fertilizer} = \left[(P_{manure})_{fertilizer}\right] - \left[Factor\_(P_{manure})_{fertilizer}\right] \tag{2.52}$$

The corrected quantity from the mineral P fertilization recommendation is estimated by either of the following equations, depending on whether only a portion (Equation 2.53) or all (Equation 2.54) of the manure is used as fertilizer:

$$corrected\_P_{\min eral\_recpoly} = P_{recpoly} - adjusted\_(P_{manure})_{fertilizer} \tag{2.53}$$

$$corrected\_P_{\min eral\_recpoly} = P_{recpoly} - (P_{manure})_{fertlizer} \tag{2.54}$$

If the quantity of adjusted_$(P_{manure})_{fertilizer}$ or $(P_{manure})_{fertilizer}$ is greater than $P_{recpoly}$, the corrected quantity of mineral P recommended to satisfy crop requirements in terms of P is considered to be zero.

4. Calculate the adjusted value of phosphated mineral fertilizers sold provincially;

Part of the fertilizer is sold for agricultural uses not covered by the indicator; primarily activities related to greenhouse and nursery operations, sod sales, and fruit and nut crops. Estimated expenditures associated with these activity sectors are based on data from CANSIM (Table 002-0044) and are available back to 2001.

$$FERTPD_{non\_accounted} = \sum_{i=1}^{n} \left[(Nb\_farms) * (averaged\_FERTPD)\right]_i \tag{2.55}$$

where:

i indexes activities related to greenhouse and nursery operations, sod sales, and fruit and nut crops.

These expenditures are then divided by the expenditures on fertilizer and lime from all agricultural sectors (FERTPD), reported in the Census of Agriculture, to estimate the fraction of FERTPD associated with these activities not covered by the indicator:

$$Fraction\_FERTPD_{non\_accounted} = \left[\frac{FERTPD_{non\_accounted}}{FERTPD_{census}} \right] \tag{2.56}$$

This fraction was calculated for Census years 2001 and 2006 only since data for expenditures on fertilizer and lime for greenhouse and nursery operations, sod sales, and fruit and nut crops were unavailable for the years prior to 2001. Therefore, the ratio of the areas of agricultural activities not covered by the indicator was used with the FERTPD fraction associated with activities not covered by the indicator, from 2001, to extrapolate the fraction of $FERTPD_{non\_accounted}$ for the Census years prior to 2001:

$$\left(Fraction*\_FERTPD_{non\_accounted}\right)_i = \left[\begin{array}{c} \left\{\left(Fraction\_FERTPD_{non\_accounted}\right)_{2001}\right\}* \\ \left\{ \frac{\left(\sum (area)_{non\_accounted}\right)_i}{\left(\sum (area)_{non\_accounted}\right)_{2001}} \right\} \end{array} \right] \tag{2.57}$$

where:

i indexes the years 1976, 1981, 1986, 1991, and 1996.

Depending on the Census year in question, the fraction of FERTPD associated with activities covered by the indicator is estimated by subtracting the $FERTPD_{non\_accounted}$ fraction (Equation 2.58) or the $Extrapolated\_Fraction\_FERTPD_{non\_accounted}$ (Equation 2.59) from the $FERTPD_{census}$ variable:

$$Fraction\_FERTPD_{accounted} = \left[FERTPD_{census}\right] - \left[Fraction\_FERTPD_{non\_accounted}\right] \tag{2.58}$$

$$Fraction\_FERTPD_{accounted} = \left[FERTPD_{census}\right] - \left[Fraction*\_FERTPD_{non\_accounted}\right] \tag{2.59}$$

In the case of the Atlantic Provinces, no values are available for specific quantities of phosphated fertilizer sold annually by province; there is only an overall value for the four Maritime provinces (NL, PEI, NS, and NB). Values for specific quantities of phosphated fertilizer sold annually by province have been estimated based on the fraction of fertilizer and lime expenditures by each province over the total expenditures of all four provinces (Census_2006 ∑FERTPD):

$$\left(P_{soldprov}\right)_i = \left[\left(P_{soldprov}\right)_{Maritimes}\right] * \left[\frac{FERTPD_i}{FERTPD_{Maritimes}} \right] \tag{2.60}$$

where:

i indexes each of the four Atlantic Provinces (NL, PEI, NS, and NB).

Thus, the adjusted value of the quantity of phosphated fertilizer sold provincially, $P_{adjusted\_soldprov}$, is estimated by multiplying the total provincial quantity sold, $P_{soldprov}$ (Equation 2.60), by the $Fraction\_FERTPD_{accounted}$ (Equations 2.58 and 2.59):

$$P_{ajusted\_soldprov} = \left[P_{soldprov}\right] * \left[Fraction\_FERTPD_{accounted}\right] \tag{2.61}$$

where:

$\boldsymbol{P_{soldprov}}$ for the years 1976 to 2001 is taken from Korol (2002) and the value for 2006 is taken from the Canadian Fertilizer Information System (CFI, 2007).

5. Calculate $P_{mineral}$, the estimated value of P for phosphated mineral fertilizers sold at the level of the polygon;

An "agronomic" ratio for a given polygon is estimated by dividing the value of the corrected recommendation for P necessary to satisfy the crop P requirements of the polygon (Equations 2.53 and 2.54) by the sum of the corrected recommendations for P necessary to satisfy crop P requirements of all the polygons within the province. This "agronomic" ratio is used with the total adjusted quantity of P sold in the province to estimate the quantity of P from phosphated mineral fertilizers sold at the level of the polygon, $P_{soldpoly}$:

$$P_{soldpoly} = \left[P_{ajusted\_soldprov}\right] * \left[\frac{\left(corrected\_P_{mineral\_recpoly}\right)}{\sum_{i=1}^{n}\left(corrected\_P_{mineral\_recpoly}\right)_i}\right] \tag{2.62}$$

where:

i indexes each of the ***n*** polygons of a given province.

The final value of $P_{mineral}$ is estimated on the basis of the agricultural area of the polygon to obtain a value that is comparable in space and time between polygons and expressed in terms of kg P ag ha^{-1}. The sum of the areas of the crops, improved pastures, and unimproved pastures of a polygon is considered the agricultural area of the polygon and estimated by the sum of the CROPLND, IMPAST, and UNIMPST variables from the Census of Agriculture. Thus,

$$P_{mineral} = \left[\frac{P_{soldpoly}}{\sum\left(CROPLND; IMPAST; UNIMPST\right)}\right] \tag{2.63}$$

Limitations and Uncertainties

Climate, cultivar selection, and producers' performance objectives may give variations in the quantities of mineral fertilizers actually used versus the agronomic recommendations for N and P. Since the calculations are based on the agronomic recommendations, these factors introduce a degree of uncertainty in the estimated value of the phosphated mineral fertilizers used in SLC polygons.

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Section 2.1.3 – $P_{removal}$

Authors

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Introduction

Part of the P introduced in the Soil Landscapes of Canada (SLC) through manure and mineral fertilizers and part of the P already present in the agricultural soils of the polygon are immobilized by crops growing in the polygon. Calculation of $P_{removal}$ is based on the assumption that, on an annual basis, a fraction of the crop P uptake during the growing season is literally excluded from the possibility of movement toward waterways during harvest. The remaining fraction of the crop P uptake returns to the polygon in the form of crop residue and is excluded from subsequent calculations, since it is directly accounted for in the P_{manure} and $P_{mineral}$ calculations. Thus, the $P_{removal}$ subcomponent estimates the annual quantity of P in crop harvests at the level of the agricultural polygon of the SLC or the watershed.

Data Sources

The calculation of crop P uptake uses crop area, crop yield data, a crop harvest ratio, and P export coefficients applicable to the crop category.

Table 2.21 lists the crops considered in the calculation. Crop areas are taken from the Census of Agriculture (see variables in Table 2.21). Yield data are taken from a working paper prepared by AAFC-AAC (Daneshfar, 2007) for all years of the Census of Agriculture (1981 to 2001) and for all the SLC polygons, with the exception of yields for corn silage, potatoes, and vegetables. Provincial yields for those three crops are taken from Statistics Canada (CANSIM, 2001a) and reallocated at the polygon level by assuming a homogenous yield for all polygons within a province. Where yield data are unavailable from the AAFC-AAC document (Daneshfar, 2007), they are estimated on the basis of three strategies. Where data for an SLC polygon are missing for all Census years, the value is estimated based on the eco-district average for each Census year. Where the eco-district average cannot be calculated, the yield value is estimated based on Statistics Canada's provincial average (CANSIM, 2001a). Where data are missing for one or more years for all polygons, the value is estimated based on Statistics Canada's provincial average (CANSIM, 2001a). Finally, where an SLC polygon is missing from the AAFC-AAC document (Daneshfar, 2007), the values are estimated based on the eco-district average of the polygon. Moreover, if the eco-district average is unavailable, the yield value is estimated based on Statistics Canada's provincial average (CANSIM, 2001a). Since not all seeded areas are harvested, a provincial harvest ratio is calculated based on the value of the harvested areas over the value of the seeded areas, both published by Statistics Canada (CANSIM, 2001b). Thus, a harvest ratio may assume a value anywhere between a minimum of 0 and a maximum of 1. The harvest ratio assigns a weight to the maximum quantity of P available for export by considering only the harvested crop fraction:

$$\left(Harvest\_Ratio\right)_i = \left[\frac{Harvested\_area}{Seeded\_area}\right]_i \tag{2.64}$$

where:

i indexes each of the ***n*** crops considered (Table 2.21).

The crop P export coefficients are taken from reference tables from the Canadian Fertilizer Institute (CFI, 2001a and 2001b) and are presented in Table 2.21.

Table 2.21. Crop-category specific export coefficients expressed in kg P per tonne yield (harvested material)

Crops considered in $P_{removal}$ calculation	Variables from Census of Agriculture (hectare)	Removal coefficients (kg P tonne^{-1})
Corn grain	CORNGRN	3.097
Corn silage	CORNSLG	2.486
Soybeans	SOYBNS	6.020
Winter cereals – fall rye and winter wheat	WHTRYE	3.686
Spring wheat	WHTSPG	4.300
Mixed grains – oats, barley, mixed grains, and spring rye	GRNCRL	3.313
Alfalfa and alfalfa mixtures	ALFALFA	2.903
Tame hay and other forage crops	OHAYFD	2.688
Potatoes	POTATS	0.457
Vegetables	TOTVEG	0.358

Methodology

The first step involves calculating the quantity of P exported by all crop harvests within the SLC polygon, using the following equation:

$$P_{exported} = \sum_{i=1}^{n}\left[\left(Area\right)_i * \left(Yield\right)_i * \left(Harvest\_ratio\right)_i * \left(removal\_coefficient\right)_i\right] \tag{2.65}$$

where:

i indexes each of the ***n*** crops considered.

The final value of $P_{removal}$ is reduced on the basis of the agricultural area of the polygon to obtain a $P_{removal}$ value that is comparable in space and time between polygons and expressed in terms of kg P agricultural ha^{-1}. The sum of the areas of crops, improved pastures, and unimproved pastures of a polygon, given by the variables CROPLND, IMPAST, and UNIMPST from the Census of Agriculture, is considered the agricultural area of the polygon.

$$P_{removal} = \left[\frac{P_{\exp orted}}{\sum (CROPLND; IMPAST; UNIMPST)} \right] \tag{2.66}$$

Limitations and Uncertainties

Only P export via field crop harvest is considered in the calculations. Phosphorus export via animal sales is not accounted for. Missing yield data that could not be estimated from the eco-district average had to be estimated using provincial yield averages. Such estimates involve considerable uncertainty, commensurate with climate and soil type variations within a province.

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- Table 001-0010 - Estimated areas, yield, production, and average farm price of principal field crops, in metric units, annual.

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- Table 001-0017: Estimated areas, yield, production, average farm price and total farm value of principal field crops, in imperial units, annual.
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Section 3 –Transport-Hydrology

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Introduction

The transport hydrology component (T_H) integrates all the different transport processes involved in the movement of phosphorus in a multiplicative and additive equation (Equation 3.2). All transport processes (surface runoff – Hortonian or from saturation excess, drainage below the root zone, and erosion) are associated with a connectivity quantification to surface water (surface drainage density, tile drainage density, and preferential flow).

Data Sources

Data sources for transport processes and connectivity subcomponents are described in the following subsections:

- Section 3.1 – Soil erosion (E) page 63
- Section 3.2 – Water balance (R & D) pages 69
- Section 3.3 – Surface drainage density (SD) pages 74
- Section 3.4 – Tile drainage density (TD) pages 78
- Section 3.5 – Topographic index (TI) pages 85
- Section 3.6 – Preferential flow pages 91

Algorithm

$$T\_H = \left[\alpha\{R(connectivity)\} + \beta\{D(connectivity)\} + \gamma\{E(DR)\}\right] \tag{3.1}$$

$$T\_H = \left[\alpha\left\{R\left(\frac{TI + SD + BF + CF}{4}\right)\right\} + \beta\left\{D\left(\frac{TD + LF + FF}{3}\right)\right\} + \gamma\{E(DR)\}\right] \tag{3.2}$$

Methodology

- ***Transport processes***

1. Surface runoff (R)

The versatile soil moisture budget (VSMB) was used to estimate surface runoff and infiltration on agricultural land. The VSMB model is a soil water-budget bucket-type model running at daily steps. Inputs of the model include weather data at the eco-district level and soil parameters from the Soil Landscape of Canada (SLC) database. The model was run with nine important crops from which Census of Agriculture (CoA) classes could be related. All data were reallocated at the SLC using a weighted average procedure. Runoff values are estimated for both snowmelt and rainfall water. For IROWC_P, daily values were summarized for each of the available Census years (1981, 1986, 1991, 1996, 2001, and 2006).

2. Drainage below the root zone (D)

The VSMB model also estimates the daily amount of excess water reaching below the root zone (between 1 m and 1.20 m). Beyond that point, the water contributes to either surface or groundwater levels. Again, for the IROWC_P, daily values were summarized for each of the available Census years (1981, 1986, 1991, 1996, 2001, and 2006).

3. Erosion (E (DR))

Erosion values were estimated using the Water Erosion Risk Indicator model (WatERI) from the Soil Erosion Risk Indicator (SoilERI) – see section 3.1. Water erosion values represent the amount of soil that is relocated within an agricultural field. Only part of this soil will leave the field to reach the streams. To quantify this, a sediment delivery ratio (DR) function of dominant landscape was applied to the soil erosion values. The corrected soil erosion values represent the integrated risk of soil particle loss due to surface runoff. As reported in CoA, erosion values are affected by land use and tillage practices. All values are reported between 0 and 1 and correspond to the significance of the risk.

- ***Connectivity factors***

1. Surface drainage density (SD)

Surface drainage density evaluates the proximity of water structures within an agricultural area. It is represented as the density of shorelines (m) per unit area (ha) calculated from the National Topographic Data Base (NTDB) available at the 1:50,000 scale developed by Geomatics Canada. The features were clipped to an agricultural mask constructed by the National Land and Water Information System (NLWIS) to link the SD component to the position of the agricultural zone in the landscape. The final values are reported on a scale of 0–1.

2. Tile drainage density (TD)

Tile drainage is used mostly in humid regions that have clayed soils and high water tables. In Canada, tile drainage is common in some provinces but its use is greatly influenced by policy. To evaluate this component, data was collected from most of the provinces. For incomplete or missing data, the general rule algorithm was used to estimate the intensity of drainage in the humid regions. This was complemented with hard data which was collected to create the index. The values represent the proportion of tile-drained land within cultivated land.

3. Topographic index (TI)

The topographic index represents the propensity for saturation excess runoff in a landscape. The TI values were calculated using the approach presented in TOPMODEL and integrated in PHYSITEL© software. All matrix values were aggregated using the zonal statistics of the agricultural land found in each SLC. A weighted average procedure was used for the SLC touching more than one watershed. The final values were reported on a scale of 0–1.

4. Preferential flow (PF)

Four distinct components are included in the PF component. Crack flow (CF), burrow flow (BF), finger flow (FF), and lateral flow (LF) are all evaluated on the SLC scale using soil characteristics, land uses from the Census data, and weather data extrapolated at the eco-district level.

- Crack flow (CF)

Crack flow represents the propensity of a combination of soil, land use, and climate data to develop cracks. This crack can intercept running water on the soil surface and serve as a preferential pathway for contaminants. Crack flow values are all reported between 0 and 1. A value of CF is reported for each Census year.

- Burrow flow (BF)

Burrow flow represents the propensity for a combination of soil, land use, land management, and climate data to support populations of *Lumbricus terrestris*. Their burrows can intercept surface runoff and serve as a preferential pathway for contaminants. A value of BF is reported for each Census year.

- Finger flow (FF)

Finger flow represents the propensity of a soil to develop rapid infiltration pathways when water accumulates at the interface between two soil layers. This usually occurs in sandy soils that have a coarser layer underlying a finer layer.

- Lateral flow (LF)

Lateral flow represents the propensity of a certain landscape to develop preferential pathways along cemented indurated horizons or large roots. A value of LF is reported for each Census year.

- ***Regression coefficients (α, β and γ)***

The IROWC_P was modeled using multiple regressions (PROC REG procedure) to determine the best linear combination of α, β and γ coefficients for R, D and E components from Equation 3.2 to explain median total phosphorus (TP) concentrations available at 88 watershed outlets across Canada. Based on the knowledge that pedology and climate are contrasted across Canada, multiple regression runs were performed using the whole water quality dataset for Canada and the respective datasets for Western Canada, i.e. British Columbia (BC), Alberta (AB), Saskatchewan (SK), and Manitoba (MB), and Eastern Canada, i.e. Ontario (ON), Quebec (QC), New-Brunswick (NB), Nova Scotia (NS), Prince Edward Island (PE) and Newfoundland and Labrador (NL), in order to find the best equations.

General Assumptions and Limitations

- The sum of uncertainties of all subcomponents
- Some spatial, some related to agricultural land

- Considered uniform across agricultural land for each polygon
- See factsheets for more detail on subcomponent uncertainties

Section 3.1 – Soil erosion

Authors

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Introduction

Soil erosion continues to be a serious threat to agricultural sustainability in Canada. The loss of soil from current and past management is a major cause of soil degradation resulting in loss of crop productivity and inefficient use of cropping inputs. Soil erosion occurs through three main processes: wind, water and tillage erosion. The combined effects of wind, water and tillage erosion pose a more serious threat than individual erosion processes.

In addition to the degradation caused by the loss of topsoil, soil eroded by wind and water is transported to agricultural drains, ditches and other waterways, where eroded soil particles increase the turbidity of the water, cause sedimentation in the waterways and waterbodies, and deliver nutrients and pesticides into the water. Although distinct from wind and water erosion, tillage erosion influences wind and water erosion by exposing the subsoil, which is more sensitive to these erosion processes, and by delivering soil to the areas of the landscape where water erosion is most intense. As such, tillage erosion also contributes to the off-site environmental impacts of soil erosion by wind and water.

Methodology

The **Soil Erosion Risk Indicator (SoilERI)**, including results, is described in Lobb et al. (2010). Technical supplements for SoilERI and its component indicators of wind (WindERI), water (WatERI) and tillage (TillERI) erosion (Li et al. 2009a, 2009b, Lobb et al. 2009, McConkey et al. 2009) provide detailed descriptions of the methods used. A summary of these documents as they related to the IROWC_P indicator is provided below.

SoilERI is used to assess the risk of soil degradation from the combined effects of the wind, water and tillage erosion on cultivated agricultural lands. This indicator and its component indicators for wind, water and tillage erosion reflect the characteristics of the climate, soil and topography and respond to changes in farming practices.

The erosion indicators provide measures of soil erosion risk based on calculated rates of soil loss. These values are separated into six classes for the purpose of analyses: negligible (less than 3 Mg ha^{-1} yr^{-1}), very low (3 to 6 Mg ha^{-1} yr^{-1}), low (6 to 11 Mg ha^{-1} yr^{-1}), moderate (11 to 22 Mg ha^{-1} yr^{-1}), high (22 to 33 Mg ha^{-1} yr^{-1}) and very high (greater than 33 Mg ha^{-1} yr^{-1}). For reporting purposes, the negligible and very low risk classes are lumped into the very low risk class. Areas in the very low risk class are considered capable of sustaining long-term crop production and maintaining agri-environmental health, under current conditions. The other four classes represent the risk of unsustainable conditions that call for soil conservation practices to support crop production over the long term and to reduce water quality impacts. The performance objective for each erosion indicator is to increase the proportion of cropland in the very low risk class and to reduce the proportion of cropland in the moderate to very high risk classes.

Soil erosion is calculated using landform data and the associated topographic data in the National Soil Data Base. Each Soil Landscapes of Canada (SLC) polygon is characterized by one or more representative landforms, and each landform is characterized by hillslope segments (upper, mid and lower slopes and depression), and each hillslope segment is characterized by a slope gradient and slope length (see Figure 3.1).

Soil erosion is calculated as the sum of tillage, water and wind erosion for each hillslope segment, using the following algorithm:

$$A_{Soil} = A_{Ti} + A_{Wt} + A_{Wd} \tag{3.3}$$

where A_{Soil} is the sum of tillage, water and wind erosion, A_{Ti} is the estimate of soil loss by tillage erosion, A_{Wt} is the estimate of soil loss by water erosion, and A_{Wd} is the estimate of soil loss by wind erosion. The interactions (non-additive effect) between different erosion processes were not considered.

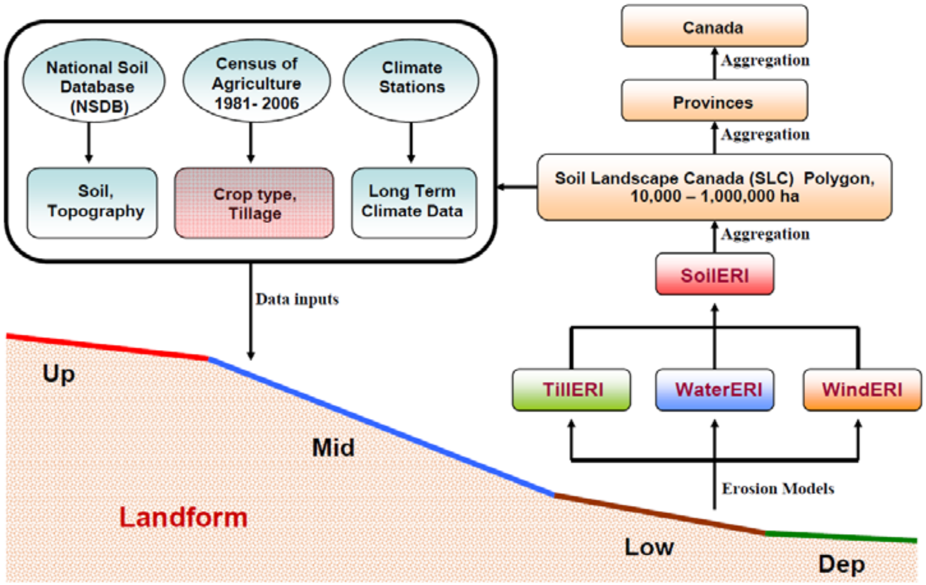

Figure 3.1. The framework of the Soil Erosion Risk Indicator (SoilERI).

Soil erosion risk by wind, water and tillage erosion is assessed as soil loss on the most severely eroding segment of a landform: the upper slope segment for wind and tillage erosion, the mid slope segment for water erosion. This is done to identify areas within cropped land that may require changes in management. The combined effects of wind, water and tillage erosion is assessed as an average soil loss over the total area of the upper and mid slope segments. The change in risk of soil erosion over time is calculated by considering the effects of changes in land use and land management practices across Canada, such as fluctuations in cropland areas, shifts in cropping systems used (crop rotations, including forages and summer fallow) and tillage systems used (conventional, conservation tillage and no-till). This information is obtained from the Census of Agriculture for 1981 onward (1981, 1986, 1991, 1996, 2001 and 2006, thus far), and also linked to each SLC mapping area. Cropping and tillage practices in the census database are grouped in classes (e.g. grain corn after soybean under conventional tillage, grain corn after soybean under no-till, etc.). The proportion of cropland falling into each of the risk classes outlined above is calculated for Canada and for each province. Changes over time in the percent value for each class in each area provides an indication of whether the overall risk of erosion is increasing or decreasing. The erosion rates are calculated for each crop-tillage combination on each hillslope segment in individual Soil Landscape of Canada polygons. For analysis and reporting purposes, the erosion rates are summed across areas to SLC polygon, provincial, regional and national levels. In IROWC_P, only the Water Erosion Risk Indicator was considered to contribute the sediment losses in the waterways.

For the **Water Erosion Risk Indicator (WatERI)**, the rate of water erosion is estimated using a model of the form of the Universal Soil Loss Equation (USLE), but incorporating the science of Revised Universal Soil Loss Equation, version 2 (RUSLE2) to account for the interactions between individual USLE factors. The algorithm used in WatERI is:

$$A_{Wt} = R \cdot K \cdot LS \cdot C \cdot P \qquad (3.4)$$

where A_{Wt} is the average annual water erosion rate, R is the climate factor, K is the soil erodibility factor, LS is the topography factor, C is the crop management factor and P is the supporting practice factor. Rainfall-runoff factor (R value) was calculated using rain gauge data from climate stations across the country. A crop sequence probability was developed to calculate the management factor (C value) for a given crop. The inherent erodibility of each soil (K value) and the slope gradient (steepness) and length factors (LS value) were firstly determined using nomograph equations and then were adjusted to equivalent RUSLE2 values using regression equations established based on thousands of test runs with RUSLE2 using data from United States counties along the United States-Canada border (Li et al., 2009b). The adjustment was made to capture the important advancements in water erosion science (e.g., the interactions between individual factors).

The total soil loss is calculated for each soil/landform/crop combination and upscaled to the SLC polygon using a weighted average procedure. Soil eroded from the eroding portion of a hillslope can be deposited at various locations before it reaches the waterways. In order to obtain the amount of sediments entering the waterways, delivery ratios need to be applied to the soil loss, in particular water induced soil loss. There are very few data about delivery ratio in the literature. In this study, three delivery ratios were developed for landforms across Canada (Table 3.1). The first delivery ratio (DelR1) is the off-slope delivery ratio, defined as the ratio of sediments leaving the hillslope over the amount of soil lost from the eroding portion of the hillslope. A fraction of the eroded soil (i.e., 1.00 - DelR1) is deposited in the lower portion of the hillslope. Values of DelR1 were originally estimated based on intensive test runs of RUSLE2 with data from three counties in the USA along the USA-Canada border, each with 3-5 soils and 5 management files, for selected landforms (Li et al., 2009b). A subset of the scenarios tested in RUSLE2 was checked with WEPP and the two programs agreed well with each other in most cases. The DelR1 values obtained from the RUSLE2 test runs were generalized for all landform types (Table 3.1). The second delivery ratio (DelR2) is the off-field delivery ratio, defined as the ratio of sediments entering waterways or waterbodies over those leaving the hillslope. DelR2 accounts for sediments stopped by the riparian zone and was assumed to be 50 % in most cases.

The third delivery ratio (DelR3) is the off-landscape delivery ratio, defined as the ratio of sediments entering waterways (therefore, directly contributes to watershed discharge) over those off-field sediments. DelR3 accounts for the internal drainage of runoff and sediments entering local depressions and wetlands. The values of DelR3 were determined based on the percent-off-site-drainage parameter derived from detailed terrain analyses of typical landforms in Canada (Li et al., 2009c). The DelR3 values were also generalized for all landform types (Table 3.1).

Table 3.1 Sediment delivery ratios estimated for the different landforms

Landform	Slope Class	DelR1	DelR2	DelR3
Inclined (i) and dissected (d)	A	0.80	0.50	1.00
Inclined (i) and dissected (d)	B	1.00	0.50	1.00
Inclined (i) and dissected (d)	C	0.80	0.50	1.00
Inclined (i) and dissected (d)	D	1.00	0.50	1.00
Inclined (i) and dissected (d)	E	0.80	0.50	1.00
Steep (s)	F	1.00	0.50	1.00
Hummocky (h) and Knoll and Kettle (k)	A	0.30	0.50	0.03
Hummocky (h) and Knoll and Kettle (k)	B	0.30	0.50	0.03
Hummocky (h) and Knoll and Kettle (k)	C	0.30	0.50	0.03
Hummocky (h) and Knoll and Kettle (k)	D	0.30	0.50	0.03
Level (l)	A	1.00	0.50	0.50
Rolling (m)	B	0.30	0.50	1.00
Rolling (m)	C	0.30	0.50	1.00
Rolling (m)	D	0.30	0.50	1.00
Ridged (r)	A	0.35	0.50	1.00
Ridged (r)	B	0.35	0.50	1.00
Ridged (r)	C	0.35	0.50	1.00
Ridged (r)	D	0.35	0.50	1.00
Terraced (t)	A	0.65	0.50	1.00
Undulating (u)	A	0.50	0.50	0.90
Undulating (u)	B	0.50	0.50	0.90

Limitations

The soil erosion indicators are subject to several limitations which affect their accuracy and uncertainty. However, results when interpreted at provincial and national scales and over multiple census dates are considered to provide acceptable spatial and temporal trends. These limitations include:

- The practices that constitute conventional, conservation and no-tillage systems are assumed to be unchanged over the duration of the analysis (25-year period, thus far). Tillage systems are also assumed to be evenly distributed amongst the crops within each SLC polygon.
- Landforms are represented in the National Soil Data Base by simple, two-dimensional hillslopes; as such, the landform data do not reflect the topographic variety and complexity that exist in real landscapes. Landforms data do not reflect the topographic complexity that exists in some landscapes nor the effect of fence lines, tree lines, roadways, ditches, and drainage ways on the slope. For some landforms, the use of these data overestimates soil loss by water erosion and underestimates soil loss by tillage erosion. Work is underway to enhance the topographic information in the NSDB for the purposes of the agri-environmental indicators.

- Wind and water erosion indicators do not account for some erosion control practices: grassed waterways, strip cropping, terracing, contour tillage and cropping, winter cover crops and shelter belts.
- The water erosion indicator does not include gully erosion that occurs where runoff concentrates. In some situations, gully erosion may exceed soil loss from more prevalent rill and inter-rill erosion. The water erosion risk should also be considered less accurate for locations with significant erosion occurring when soils are frozen. In particular, the erosion risk from rainfall occurring on thawed soil layer overlying frozen soil is likely underestimated.
- There is very little experimental data with which to calibrate soil erosion indicator models in Canada, and only a few sites in Canada where these models can be adequately validated. In order of decreasing validation, the erosion indicators are ranked: tillage, water, and wind.
- Erosion indicator models assess the risk of soil loss within cropped land, and do not assess the risk of off-site impacts. The linkages between the erosion indicator models and the risk of off-site impacts of soil erosion were established through the three delivery ratios developed in this study (Table 3.1). However, these delivery ratio values were mostly based on model simulations or experts' best assessments and have not been validated against field measurements. Therefore, Table 3.1 was considered to be preliminary at this stage. Further studies are clearly needed to improve the accuracy of the delivery ratio values.
- The erosion indicator models provide annual average values. They cannot provide any greater temporal detail. As such, they may only serve as reference data in validating other indicator models with greater temporal resolution, such as the IROWCP indicator.

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Section 3.2 – Water balance (runoff / deep drainage)

Author
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Introduction
Soil water is a key factor in the partitioning of precipitation into canopy interception, surface runoff, soil water storage, evapotranspiration and deep drainage. The effects of spatial and temporal variations in the water balance components are, however, not only purely hydrological. Biological and chemical processes are critically dependent on the soil water status. Plant growth and crop development are directly related to the time-depth status of the soil water profile. Movement and transformation of agrochemicals (e.g. phosphorus, nitrogen and pesticides), and the resulting chemical composition of surface and ground- waters, is determined by solute transport mechanisms, which are directly related to water moving in and through the soil profile.

Methodology
The Versatile Soil Moisture Budget (VSMB) model, originally developed by Baier and co-workers (Baier and Robertson, 1966; Baier et al., 1979; Baier et al., 2000) and later adapted by Akinremi et al. (1996), was used to estimate soil water contents and components of the soil water balance (i.e., potential and actual evapotranspiration, surface runoff, and deep drainage) under annual and perennial crops. The model calculated the soil water budget resulting from precipitation, rainfall interception, surface runoff, evapotranspiration and deep drainage. Each day of the year, the net loss or gain was added to the water already in the soil. Water was withdrawn at different rates from different depths in the soil profile, depending on the rate of potential evapotranspiration, the stage of crop development, the water release characteristics of the soil, and the available soil water content.

The soil profile was divided into six layers representing, from the surface downward, 5%, 7.5%, 12.5%, 50%, 75%, and 100% of the rooting depth. Each layer was characterized by a saturation-, field capacity- and permanent wilting point- water content. In the modified VSMB (Akinremi et al., 1996), water from precipitation cascaded from upper to lower layers when the upper ones reached field capacity; moreover, upward and downward redistribution of soil water was simulated using an algorithm adapted from the Ceres-Wheat model (Ritchie and Otter, 1985). Akinremi et al. (1996) also improved the surface runoff subroutine for rainfall and snowmelt (see below).

The rate of water uptake was simulated by using depth-dependent crop coefficients (Baier et al., 1979; De Jong and MacDonald, 1975) that changed as the crop progressed through different phenological growth stages. Planting dates of annual crops were estimated according to procedures described by Bootsma and De Jong (1988) and De Jong et al. (2001). The duration of each growth stage (planting to emergence, emergence to full cover, full cover to senescence, senescence to harvest, and harvest to the next planting date) was defined by a biometeorological timescale model (Robertson, 1968) for cereals, and by accumulated growing degree days for corn, soybeans, and potatoes (Shaykewich et al. 1998; De Jong and MacDonald, 1999). Growing season start and end dates of perennial crops were determined using the procedures described by Sly (1982). For perennial grass and alfalfa, we used the crop coefficients suggested by Baier et al. (1979), distinguishing between the growing season and the non-growing season. For rangeland, we used the monthly crop coefficients reported by De Jong and MacDonald (1975).

Soil water release characteristics, as defined by Dyer and Baier (1979), were similar to those used by De Jong and Bootsma (1988). For coarse, medium, and fine textured soils, curves 1 (concave), 2 (linear), and 4 (convex) were used, respectively. Coarse textured soils were defined as having between 40 and 65% sand, fine textured soils as having between 65 and 80% clay, with medium textured soils forming the remaining textural spectrum. Following Gallichand et al. (1991), the R value (i.e., the plant-available water content at which the actual evapotranspiration rate fell below the potential rate) was crop dependent. Based on data reported by Van Keulen and Wolf (1986) and Allen et al. (1998), R values ranged from 0.65 for potatoes (i.e., a relatively drought-sensitive crop) to 0.40 for alfalfa (i.e., a more drought-resistant crop).

Following Akinremi et al. (1996), the soil surface temperature was calculated using an algorithm adapted from the EPIC model (Williams, 1995) which considered the insulating effect of snow cover. The five-day running mean surface temperature, calculated from daily maximum and minimum air temperatures, was corrected for snow cover by a lag factor that varied exponentially between 0, when there was no snow cover, and 1.0 with a snowpack of 12 cm. It was assumed that the soil was frozen when the calculated soil surface temperature was below 0°C.

Surface runoff from frozen soil was calculated according to the procedure outlined by Ash et al. (1992). When the soil was not frozen, the Curve Number (CN) technique was used (Soil Conservation Service, 1972). The runoff curve number was determined from a matrix using information on land use (i.e., small grain crops, fallow land, pasture, close-seeded crops, and row crops), hydrological condition (i.e., good, fair, and poor), and soil hydrological groups (A, B, C, and D). Following Bolinder et al. (2000), the latter was based on the soil drainage class and the rooting depth of the profile. The hydrological condition (which attempts to quantify the state of vegetative cover of similar crops) of perennial crops was considered to be good during the growing season and fair during the non-growing season. For annual crops, the hydrological condition between emergence and full cover was assumed to be fair, and between full cover and harvest it was assumed to be good. For the period between harvest and the next emergence in spring, the curve number for annual crops was selected to be that for fallow land.

The VSMB was further modified by including rainfall interception calculations, according to the procedures of Feddes et al. (1978), whereby interception is a function of daily rainfall and the degree of soil cover. The latter varied from one crop to the next and with the progression of the crop growing season.

The snow budgeting procedure, described by Baier et al. (1979), was used during the winter to estimate soil water content in early spring. This procedure allowed us to simulate continuous runs for 31 years without re-initializing the program every year. For each soil layer, the model started with an assumed soil water content at 75% of the maximum possible on April 15, 1975. The outputs from the initial simulation year (1975) were not included in subsequent analyses of the VSMB output data.

Data Sources

- ***Input for the VSMB***

Soil water content was estimated at the soil series (or soil component) level for each Soil Landscape of Canada (SLC) polygon, with 2780 SLC polygons covering the agricultural farmland area of Canada (Soil Landscapes of Canada Working Group, 2006). The calculations were made for summerfallow and eight crop types (i.e., spring cereals, canola, grass, rangeland, alfalfa, corn, soybeans, and potatoes) for all soil series within each SLC. The results were scaled-up to the SLC polygon level (De Jong et al. 2009).

Weather data, including daily maximum and minimum air temperatures (°C) and daily precipitation (mm) for the period 1975 to 2005, were obtained from Agriculture and Agri-Food Canada's eco-district climate database (1:7,500,000 map scale) described by Xu et al. (2010). It was assumed that all SLC polygons falling within an eco-district would have the same weather. Total precipitation was divided between rain and snow based on the work of Bélanger et al. (2002). Daily potential evapotranspiration (mm) was calculated using the technique of Baier and Robertson (1965).

Soil data were obtained from the Canada Soil Information System (CanSIS), Soil Landscapes of Canada, version 3.1 (Soil Landscapes of Canada Working Group, 2006). Soil landscape data, including the area of each soil series within the SLC, drainage class, and rooting depth, came from the National Soil Component Table for each soil series within an SLC. Soil series profile data, including saturation water content and water content at 10, 33, and 1500 kPa tension, interpolated to the appropriate depths used in the VSMB, were obtained from the CanSIS National Soil Layer File. For coarse textured soils, it was assumed that field capacity water content occurred at 10 kPa tension. For all other soils, field capacity water content was set at 33 kPa.

The acreage of 27 agricultural crops was collected once every 5 years (1981, 1986, 1991, 1996, and 2001) by Statistics Canada through the Census of Agriculture, and these data were allocated to the SLC polygons (Huffman et al., 2006). Nine major crops, which together represent between 80 and 100% of the SLC farmland area in 96% of all SLC polygons, were used in the VSMB. In the years when no Census data were collected, crop acreage was obtained by extrapolation and linear interpolation.

Limitations

The soil water balance calculations are subject to several limitations that affect the accuracy and uncertainty of the results. However, when interpreted at the SLC scale over multiple census years, the results provide reasonably accurate spatial and temporal trends. The limitations include:

The VSMB model was developed for free draining soil profiles, i.e., it does not deal with fluctuating groundwater tables. Fortunately, in the more arid regions of Canada, most of the agricultural land is underlain by watertables that are well below the rooting depths of crops. In the more humid regions, tile drainage of agricultural land is a common management practice that prevents the watertable from entering the root zone.

The soil water balance was not calculated for 26 SLC polygons because of missing and/or faulty soil physical data. Organic soils were excluded because the concepts of field capacity and wilting point, as employed in the VSMB, were not applicable. Most of the polygons with missing soil information were located in Quebec.

The Curve Number (CN) technique, which separates precipitation into its runoff and infiltration components, depends on a large bank of empirical data for watersheds and land use patterns within the USA. It has a limited physical base in the processes that govern infiltration. Optimisation procedures can be used to estimate improved CN values for experimental catchments (Perrone and Madramootoo 1998).

Winter, associated with snow cover and frozen soil, plays a significant role in many hydrological systems. The VSMB is focused on the snow budget (i.e., snow accumulation, snow drift, snow melt, etc.), but ignores to simulate the physics of water and heat transfer in snow-soil system.

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Section 3.3 – Surface drainage

Authors

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Introduction

The surface drainage component is one of the connectivity factors used in the Transport-Hydrology component of the IROWC_P (Equation 3.2). Field distance to waterbodies is generally used to illustrate the vulnerability of streams to phosphorus contamination (Gburek et al. 2000). However, since this information is often not available regionally, the drainage density index was introduced. In hydrology, drainage density is defined as the total length of drainage structures found in a given area and is usually calculated using concentration of flow, derived from terrain properties (Dobos et al., 2005). Drainage structures can be either naturally formed or constructed to serve the needs of a population. Low drainage density values represent ridges where little dissection of the landscape occurs while high values represent valley bottoms that are highly dissected.

Algorithm

The hydrographical network consists of lines and polygons representing the main rivers, brooks, lakes, and ponds found on the SLC polygon. Depending on the scale of the source data, the density of the network can be very important. To represent the risk of contamination of the water bodies, we calculated the length of the shorelines and the segments aggregated to the SLCs. The total length of shorelines per hectare serves as the surface drainage density index for the IROWC calculation.

$$SD = \left\{ \frac{[Length\_of\_WC * 2] + [Lenght\_of\_WB\_WT]}{AGR\_Hectares} \right\} \tag{3.5}$$

where:

Length_of_WC (watercourses) represents total length of all linear features with two shores that can be in contact with agricultural land;

Length_of_WB_WT represents total perimeter of all waterbodies (*WB*) and wetland (*WT*) polygons features;

AGR_Hectares corresponds to the area of agricultural mask polygons found in each SLC (Total).

Data Sources

In order to maintain precision consistently on a national scale, the hydrographical data were extracted from the National Topographic Data Base (NTDB) published by Natural Resources Canada (NRCan) at the 1:50,000 scale. A specific agreement was concluded between National Land and Water Information System

(NLWIS) and NRCan to provide access to the database for all NAHARP projects[1]. The coverage comes from old 1:50,000 topographic mapsheets and is validated with photo interpretations of the region. The data are separated according to the represented object. First, all small brooks and rivers are represented using a single line (segment) which connects all features of the network. A polygon feature class representing waterbodies includes lakes, ponds, and rivers that are large enough to be represented at the 1:50,000 scale. Finally, another polygon feature class represents all types of wetland (without specifications).[2] The NLWIS team, and our team, pre-processed the data so that all datasheets could be appended together to provide uniform coverage of the agricultural area.

General Assumptions and Limitations

Conceptually, the main limitation concerns the linking of shorelines to the agricultural land. In some polygons, the sensitive areas may be located upstream of the agricultural areas; while the calculated risk may be high, there is actually no, or limited, contamination possible. To address at the best this limitation, SD was only calculated on the intercept of the hydrographical network and the agricultural mask (proposed coverage of agricultural land in Canada) of the SLC polygons.

Of course, the final values for drainage densities are affected by the scale of the input values. When a uniform data source is used for the entire country, the impact of this scale can be reduced. However, the numeric topographical data comes from a variety of sources and can be affected by the precision of available data. Also, open ditches used for drainage practices, which can play an important role in hydrological connectivity, are missing from the scale used in these calculations.

The numerical features are also time dependent. Some features may have evolved over time, especially in areas with great anthropogenic pressure. For example, newly constructed drainage systems, land filling, or wetland drainage may have occurred and would not be integrated into the database. Another limitation concerns the borders of the wetlands. The definite shorelines of a wetland can fluctuate greatly from year to year and this could affect the accuracy of the surface drainage density index.

Methodology

- ***Data needed***
  - The SLC polygons for the different provinces (longitude/latitude coordinates). The ARC/INFO Shapefile formats in decimal degrees (DD) (pr3dd.shp). [Online] Available: Canadian Soil Information System-http://sis.agr.gc.ca/cansis/.
  - The National Topograhic survey mapsheets covering the agricultural area of the province. The ARC/INFO Shapefile formats: MAPNO_water_c_1.shp, MAPNO_water_b_a.shp, and the MAPNO_wetland_a.shp were used to determine the connectivity to the water bodies.
  - Agricultural SLC for each province. ARC/INFO Shapefile formats.

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[1] Now publicly accessible at http://www.nrcan-rncan.gc.ca.

[2] A wetland is an area where the land is submerged for a significant amount of time during a year.

- ***Geoprocessing methodology***

1. Append all the mapsheets to obtain a complete file covering all the agricultural areas of the province. This step should be repeated for the water bodies, the wetland and watercourses contained in the database;
2. Combine all polygon features (water bodies and wetlands) to eliminate superposition of the datasets; this improves our ability to calculate the length of shorelines for polygon features;
3. All line or polygon features of the dataset should be projected in a conform projection ellipsoid before calculating the length;
4. Convert all polygon features to polylines;
5. Intersect the resulting shapefile to the agricultural mask layer aggregated at SLC;
6. Clean out all lines that do not represent lakes or wetland contours;
7. Calculate the length of the segments of the shapefile;
8. Summarize the resulting file using the SL number and add up the length for each SL
9. Repeat steps 5 to 8 for the watercourse file;
10. Surface drainage density corresponds to the total length of shorelines (m) divided by agricultural area (hectares). The agricultural area is evaluated using the agricultural mask area found in each polygon.

- ***Rescaling procedure:***

Rescaling was performed by dividing SD values by the 99th percentile SD. All values above the 99th percentile were given the value of 1.

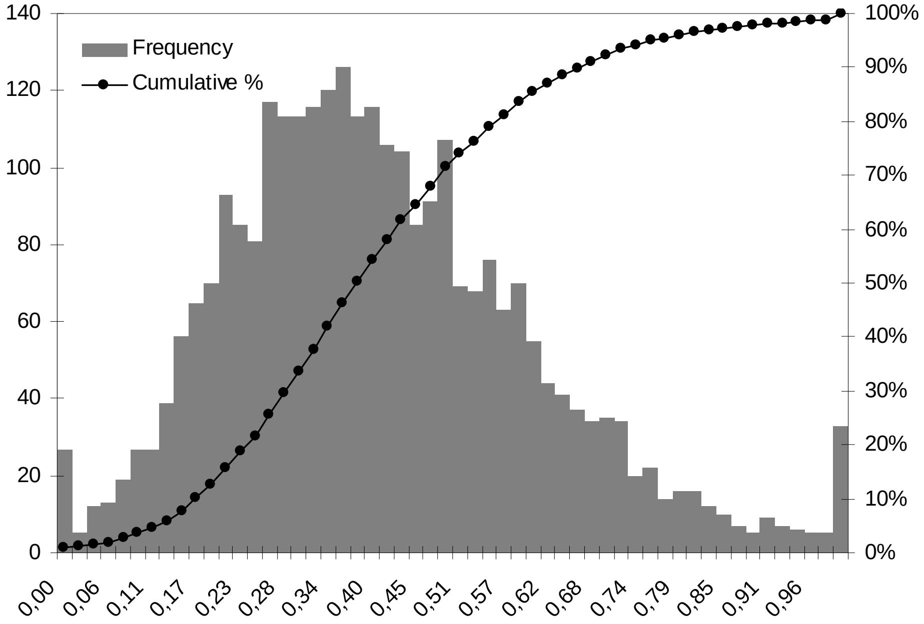

Figure 3.2. Histogram of the distribution of the rescaled SD values for the 2780 polygons

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Section 3.4 – Tile drainage

Authors
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Introduction

Subsurface drainage systems reportedly play an important role in carrying contaminants to water bodies (Sims et al., 1998). Subsurface drainage improves the infiltration of water by reducing the amount of water in the soil between precipitations. It has been shown that subsurface drainage may represent the dominant hydrological process on tiled surfaces (Enright and Madramootoo, 2004) to reduce the risk of surface runoff and water erosion. However, recent research indicates that infiltrating water can transport significant amounts of dissolved, and even particulate forms, of P through leaching and preferential flow processes, especially on P-rich soils (Sims et al., 1998; Beauchemin et al., 2003; Kinley et al., 2007). These levels are reported to be consistently over the 0.03 mg L^{-1} threshold in Quebec for soil presenting low P-sorption capacity (Beauchemin et al., 2003). In Nova Scotia, water quality at the drain outlet showed that 98% of the fields monitored, and 55% of the samples, had concentrations above 0.03 mg L^{-1} (Kinley et al., 2007). The higher values were usually associated with high flow rates.

To quantify the risk associated with the presence/absence of tile drainage systems, we assessed the intensity of tile drainage practices in specific landscapes. Information on tile drainage is under provincial jurisdiction and these data had never been integrated by a federal institution. We collaborated with soil specialists to collect data from each province which was dissimilar and could not be integrated into one file. Each data source will be examined separately and each index will be validated by an expert before we can proceed to formulate an IROWC_P model.

Data Sources

- ***British Columbia***

The location of subsurface drainage systems are not recorded by any public institution in British Columbia. However, based on expert knowledge, this agricultural practice covers about 20,000 ha mainly in the lowlands of the Fraser Valley and on the east coast of Vancouver Island.[1]

- ***Alberta and Saskatchewan***

Local authorities in Alberta and Saskatchewan have not encouraged subsurface drainage systems, so only a few projects exist in these provinces. A total of 8500 ha has been reported to local authorities and their

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[1] David Lobb, personal communications 2007.

attributes recorded with UTM coordinates. This information will be used directly to create a TD index for each province.

- ***Manitoba***

Subsurface drainage systems are not popular in Manitoba and no projects are recorded by the authorities. We consider that no tile drains are installed in this province.

- ***Ontario***

Ontario is presently collecting information on land parcels that are either systematically or randomly drained. This information will be used to update soil characteristics in pedology databases. There are approximately 2,000,000 ha of land with subsurface drains installed. At present, 835,000 ha of this land have been digitized but some counties are missing entirely from the analysis. These data, although of good quality, may be incomplete and therefore insufficient to produce a provincial index.

- ***Quebec***

In Quebec, policies encouraging subsurface drainage practices were implemented in the late 1960s and maintained until the early 1980s. Considerable information was collected and summarized in different reports but there is no up-to-date public information. From the documents we received, 700,000 ha out of an estimated 1,000,000 ha were reported on a county basis and only 169,000 ha were reported on a municipality basis. Again, these data can not create an index but only be used to supplement using the general rule.

- ***New Brunswick and Nova Scotia***

No information regarding the localities of tile drainage has been collected by provincial authorities. However, experts expect that subsurface drainage practices cover about 15,000 ha in New Brunswick and 25,000 ha in Nova Scotia.

- ***Prince Edward Island***

Soil pedologist, Delmar Holmstrom, has assessed the extent of drainage systems installed on the main soil types in the province. This information will be used directly to create a TD index for the province.

- ***Newfoundland and Labrador***

No data on subsurface drainage practices have been collected. A table in Appendix 2 presents the estimated and spatially distributed areas under systematic drainage.

General Rule Algorithm

For provinces where spatial information on tile drainage does not exist, or is incomplete, a general algorithm was used to derive the probability of subsurface drainage installed in each SLC.

$$\text{TD:}\quad \text{IF}\left\{ \text{IMPERFECT} >= 90\ \%,\ \frac{\left[\dfrac{\sum\limits_{i=1}^{n}(\text{SumAnnual Crop})_i}{n}\right]}{\mathit{TFAREA}},\ \frac{\left[\left[\dfrac{\sum\limits_{i=1}^{n}(\text{SumAnnual Crop})_i}{n}\right]-\left[\left(\dfrac{100-\mathit{IMPERFECT}}{100}\right)*\left(\mathit{TFAREA}\right)\right]\right]}{\mathit{TFAREA}} \right\} \tag{3.6}$$

*** only positive values are considered

where:

***IMPERFECT*:** sum of covering percentage of soil component presenting drainage characteristics lower than imperfectly drained[1] soil inclusively;

***n*:** corresponds to Census years 1–5;

SumAnnualCrop: annual crop surfaces in the SLC during the 1981–2001 period;[2]

***TFAREA*:** Total farm area (hectares) = Crop Land [CROPLND] + Improved Pasture [IMPAST] + Unimproved pasture [UNIMPST].

General Assumptions and Limitations

Annual crops are usually grown on soils that have few limitations to their use. Using the CanSIS database, we found it difficult to reallocate the crops into a polygon according to most suitable crops. Therefore, our methodology assumes that annual crops will be grown preferably on soils without limited drainage. Of course, from the Census data, a certain number of crops that are sensitive to drainage are not clearly represented by any of the classes. Such classes are considered to be annual crops and are presented in Appendix 1.

The SLC database considers only major soil groups found in a region; the areas covered by these soil groups are estimated. For large polygons, a 1% change results in hundreds or thousands of hectares of agricultural land. Because the area of polygons varies greatly, the reliability of the information also varies. Also, because minor soil groups are absent from the database, the extent of poorly drained agricultural soils is not considered in our calculations.

Provincial policies have had a great impact on the development of tile drainage practices. Quebec and Ontario, for example, subsidized extensively the implementation of drainage systems during the 1960s and 1970s. For these two provinces, some soils with minor drainage problems may have been systematically tile drained during those years. Because these soils would not be integrated using the general rule, the results for Ontario and Quebec were completed with only the recorded data.

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[1] Soil drainage classes: imperfectly drained, poorly drained, and very poorly drained (CanSIS, Soil Name File (SLC version 3.0)).

[2] See Appendix 1 for a complete definition of mean annual crop.

For some provinces (Quebec and Ontario), the general rule results can be compared to recorded data. However, for other provinces (British Columbia, New Brunswick, Nova Scotia, and Newfoundland) there are no data available to validate the results, so expert opinions are needed.

The TD subcomponent accounts for only systematic drainage systems; thus it will always underestimate the actual implementation of drainage systems on farm land. The randomly designed drainage systems are harder to locate because they constitute small areas of agricultural land. They were usually installed without public funds, so they are often not recorded.

Methodology

- ***Data needed***
  - The SLC polygons for the different provinces (longitude/latitude coordinates) with the ARC/INFO Shapefile formats in decimal degrees (DD) (pr3dd.shp). [Online] Available: Canadian Soil Information System-http://sis.agr.gc.ca/cansis/.
  - The agricultural SLC for each province used for the NAHARP calculations and the ARC/INFO Shapefile formats.
  - Census of Agriculture database (CoA-1981, 1986, 1991, 1996, and 2001).

- ***Estimation methodology***

  1. Calculate the extent (as percentage of coverage) of imperfectly, poorly, or very poorly drained soils. This table includes the polygon number (unique value) and the sum of poorly drained components (Poor_drainage.dbf);
  2. Calculate the extent (in hectares) of annual crops into polygons for the 1981–2001 period. Calculate the average area of annual crops in the SLC (Annual_Crops.dbf);
  3. Join the two table based on their SLC number
  4. Calculate the estimated TD area based on equation 3.6. For BC, only the agricultural polygons of the Fraser Valley and the east coast of Vancouver Island were selected according to expert advise;
  5. The results were compared with expert’s estimations of the total drained area in each province (appendix 2).

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Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. **27**:277–293.

Appendix 1. List of Census fields and corresponding crops

OTHFLD: area of other field crops: canary seed, millet for grain, caraway seed, ginseng, coriander, and others.
CORNGR: area of corn for grain.
CORNSLG: area of corn for silage.
GRNTOT: total grains including: oats, barley, mixed grains, rye, buckwheat, and triticale.
OILSD: total oilseeds including: canola, flaxseed, mustard seed, sunflowers, and safflower.
POTATS: area of potatoes.
SUGARB: area of sugarbeets.
TOBACO: area of tobacco.
TOTVEG: area of all vegetables.
SOYBNS: area of soybeans.
PULSE: area of pulse legumes including: dry field beans, dry field peas, white beans, lentils, fababeans, chic peas, and other dry beans.
FRTBRY: area of fruit berries.
FRTGRP: area of fruit grapes.
PERAGR: percentage land area in agricultural use.

$$\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{SumAnnualCrop})_{\mathrm{i}}}{n} = \left[\frac{\sum_{i=1}^{5}\left\{\begin{matrix}(OTHFLD)_i+(CORNGR)_i+(CORNSLG)_i+(GRNTOT)_i+(OILSD)_i+(POTATS)_i+(SUGARB)_i+\\ (TOBACO)_i+(TOTVEG)_i+(SOYBNS)_i+(PULSES)_i+(FRTBRY)_i+(FRTGRP)_i\end{matrix}\right\}}{5}\right]$$

where:

i corresponds to Census years1 through 5;

the number 5 is the number of CoA (1981, 1986, 1991, 1996, and 2001).

Appendix 2. Estimated and spatially distributed areas under systematic drainage

Province	Estimated sub-surface drained area (ha)	Data collected	Soil Landscape of Canada database (SLC) tile drainage (TD) estimation methodology	SLC TD estimation drained area (ha)	Percentage of drained area (%)
BC	19,100	No data collected	Generic rule applied in lowland of Fraser Valley	24,038	125
AB	12,900	Punctual project values	Sum of all punctual values in each polygon	5793	45
SK	10,000	Punctual project values	Sum of all punctual values in each polygon	316	3.1
MB	1000	No data collected	---	0	0
ON	1,994,000	Digitalized parcels	Generic rule + corrections for collected values	1,976,044	99
QC	1,000,000	Record of drained area per municipalities for 1976–1980	Generic rule + corrections for collected values	761,124	76
NB	14,600	No data collected	Generic rule	5799	40
NS	24,300	No data collected	Generic rule	8343	34
PE	1650	Area of drained land associated with soil type	Linkage of soil types-drained values	3237	196
NF	>0	No data collected	---	0	
TOTAL	3,077,550			2,784,694	90

Section 3.5 – Topographic index

Authors

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Introduction

Saturation excess runoff is one of the dominant hydrological processes in temperate and humid climates. This type of runoff is usually driven by the topography in gently-sloped areas that have shallow soils on top of impermeable bedrock or impervious soil layers (Figure 3.2). For these areas, and under these specific conditions, the surface runoff process can be predicted with an index of hydrological similarity based on topographic considerations. According to the topographic index (TI) introduced by Beven and Kirkby (1979), all topographic units or spatial elements of a watershed with an identical index value develop, in principle, the same conditions for saturation, surface, and subsurface flow/runoff.

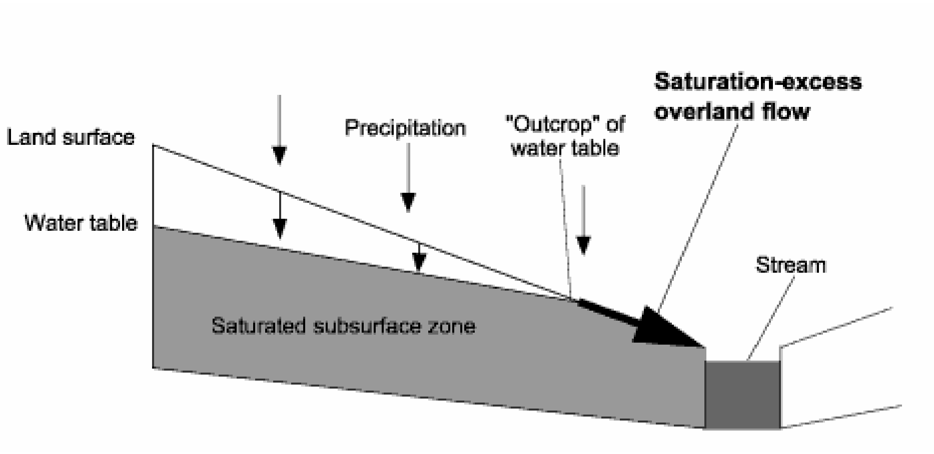

Figure 3.3. Saturation excess overland flow

Algorithm

$$TI_i = \ln\left[\frac{a_i}{\tan(\beta_i)}\right] \tag{3.7}$$

where:

TI_i is the topographic index calculated at point *i*. High values will be caused by either a long slope or upslope contour converging with low slope angles, and the corresponding areas will tend to saturate first;

a_i is the upslope area per unit of contour length draining through the point (i). This area is calculated using a flow accumulation algorithm along the watershed terrain. By comparing a set of previously reported flow direction algorithms, it appeared that the D8-LTD (Orlandini et al., 2003) is the best suited one for determining the drainage network. However, all these algorithms have trouble defining flow directions in areas with low surface gradients (Garbrecht and Martz, 1997) which often makes it difficult to calculate TI. As a consequence of this difficulty, the modelled flow direction may not match the river network location. To bypass this problem, Turcotte et al. (2001) developed a method using digital river and lake networks (DRLN) as inputs in addition to the digital elevation model (DEM) to correct the modelled flow directions. The use of an initial reconditioned DEM, by a “burning” procedure, to force drainage to the most plausible position of streams within the landscape is necessary, especially in flat areas. We strongly recommend eliminating pits before implementing the flow direction algorithm;

β_i is the local topographical slope angle acting at point *i*. The hydraulic gradient of the saturated zone can be approximated by the local surface topographical slope, measured with respect to plan angle (in degree) tan(B).

From the resulting matrices, intersections of the values with the SLC polygons are made and the statistics calculated (using zonal statistics of ArcMap 9.2 Spatial Analyst Extention). The weighted average of all watersheds is then calculated for each SLC polygon that is considered to be agricultural.

$$AVG\_TI = \left[\frac{MeanTI * AREA}{\sum AREA} \right] \tag{3.8}$$

where:

AREA is the pixel resolution x number of pixel falling within a SLC polygon.

General Assumptions and Limitations

The first assumption, which views the dynamics of the saturated zone as successive steady states, implies that there is a constant recharge rate and a downslope flow for all hillslopes; clearly, this assumption is false for hillslopes that are seasonally dry. Under these dry conditions (Beven, 1997; Beaven et al., 2001; Blazkova et al., 2002): (i) the effective upslope contributing areas do not extend to the hillslope divide or boundary, and (ii) the saturated zone may become localized and isolated and so be ineffective. Hence, in watersheds where there is a long dry season and a long wetting-up period, the dynamics or lack of steady-state saturated flow conditions will either restrict the use of TOPMODEL, or highlight the fact that the dynamics of the contributing areas govern the hydrological behaviour of the watershed. The potential occurrence of the runoff at saturation as evaluated by TI still needs to be validated in different regions of Canada.

The second assumption is that the water table is nearly parallel with the surface topography for relatively thin soils over an impermeable soil layer on moderate slopes. Under this condition, the hydraulic gradient is assumed to be equal to the slope angle. However, this behaviour will change for deeper soils or if there is a strong spatial or temporal change in the recharge rate (Beven and Freer, 2001).

The TI values are calculated for every pixel on a hillslope and statistically aggregated to the SLC scale. Initially, during this process, lakes that have naturally high TI values were still considered and contributed to the overestimation of the risk of saturated runoff from the agricultural fields. This result illustrates a conceptual limitation, which is found in other components, regarding the position of the agricultural fields in the landscape relative to other spatially bound indexes. To minimize the impact of this conceptual limitation, only TI values of pixels intercepted by the agricultural mask, created by the National Land and Water Information Service (NLWIS), were used to obtain a general TI value for a SLC polygon.

Methodology

- ***Data needed***

  1. Linear network of stream oriented downstream associated with lake polygons (Appendix 1);
  2. Mosaic DEM clipped to watershed contours using 1:50,000 Canadian Digital Elevation Data (CDED) from GeoBase. [Online] Available: GeoBase-http://geobase.ca/;
  3. List of agricultural polygons that will be used for the NAHARP calculations;
  4. The agricultural mask layer from the National Land and Water Information Service (NLWIS).

- ***Data preparation***

  1. Preparation of the DEM
     - Create an index of the mapsheets
     - Convert CDED to DEM rasters
     - Mosaic DEM
     - Project DEM in Lambert Conic projection using uniform pixel size (20m – Resampled output raster with bilinear interpolation)
     - Clip DEM to watershed contours
     - Convert results to ASCII
  2. Preparation of hydrographical networks to be used by PHYSITEL
     - Get central line network of hydrographical data
     - Set flow direction and flip lines according to flow direction
     - Delete river polygons
     - Erase network features under lakes
     - Add nodes to lakes
     - Clean final network to respect PHYSITEL capabilities

- ***Topographic index calculations***

    1. DEM pre-processing by a "burning" procedure and a sink removal algorithm;
    2. Computation of the slope by applying a slope algorithm on the original DEM;
    3. Implementation of the flow direction algorithm on the reconditioned DEM;
    4. Determination of the flow accumulation;
    5. Calculation of the TI values.

- ***Calculation of aggregated values i***

    1. Preparation TI index of rasters
        - Convert TI matrix in ESRI rasters
        - Define projection of rasters
    2. Create zonal statistics tables for each SLC
        - Use zonal statistics from the Spatial Analyst Extention on the agricultural mask polygons intersected and dissolved for each SLC
        - Create a summary table of all resulting output files

- ***Rescaling procedure:***

Rescaling was performed by dividing AVG_TI values by the 99th percentile of its distribution. All values above the 99th percentile were given the value of 1.

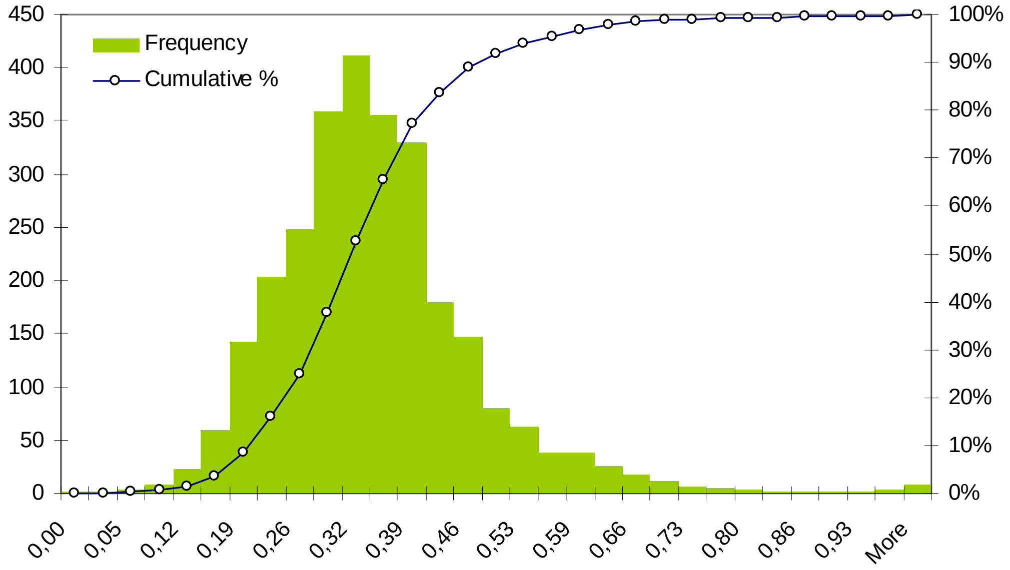

Figure 3.4. Histogram of distribution of the rescaled AVG_TI values (n = 2780 polygons).

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Appendix 1. Data sources of the hydrological network

Province	Hydrographical data source	Hydrographical data scale	Contact information
BC	BC watershed project	1:20,000 and 1:50,000	BC Ministry of Sustainable Resources http://aardvark.gov.bc.ca/apps/dwds/acceptTerms.do
AB	National Topographic Data Base (NTDB)	1:50,000	Natural Resources Canada http://www.cits.rncan.gc.ca
SK	Saskatchewan watershed project	1:50,000	Saskatchewan Environment http://gisweb1.serm.gov.sk.ca/mapserver/ssn/downloads/version2/master_ssn.htm
MB	Index of drain lines	1:20,000	Manitoba Land Initiative https://web2.gov.mb.ca/mli/
ON	Virtual hydro lines	1:20,000	Mike Robertson, Land Information Ontario mike.robertson@ontario.ca
QC	MDDEP oriented hydro network	1:20,000	Daniel Blais, Ministère du Développement Durable, Environnement et Parc daniel.blais@mddep.gouv.qc.ca
NB	NTDB	1:50,000	Natural Resources Canada http://www.cits.rncan.gc.ca
NS	NTDB	1:50,000	Natural Resources Canada http://www.cits.rncan.gc.ca
PEI	NTDB	1:50,000	Natural Resources Canada http://www.cits.rncan.gc.ca
NF	NTDB	1:50,000	Natural Resources Canada http://www.cits.rncan.gc.ca

Section 3.6 – Preferential flow

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Introduction

Preferential flow (PF) refers to the non-uniform movement of water with dissolved and/or suspended material through preferred pathways such as earthworm burrows, desiccation cracks, along lateral boundaries, and root channels in soil. It prevents contaminants from mingling with the soil matrix solution and minimizes the retention time in soil that is necessary for surface exchange, catalysis reaction, and biodegradation (Bergström et al., 2001). Preferential flow accelerates the transport of pollutants to ground and surface waters and is therefore included in the T_H component of risk indicators of water contamination by P (IROWC_P). Four types of PF processes have been recognized: 1) crack flow (CF), 2) burrow flow (BF), 3) finger flow (FF), and 4) lateral flow (LF). The objective of the PF sub-component is to predict the likelihood of PF occurrence by these flow processes on the scale of Soil Landscape of Canada (SLC) polygons (1: 1,000,000) across Canada.

Data sources

The data were obtained from the National Soil Layer File (nationalslf311.dbf) and National SLCv3.1.1 Component Table (nationalslc311cmp.dbf) of Soil Landscapes of Canada, version 3.1.1 (Soil Landscapes of Canada Working Group, 2007), the Census of Agriculture database (1981–2001), Versatile Soil Moisture Budget (VSMB) model (Akinremi et al., 1996), provincial and/or federal tile drainage data sets provided by local experts, climate data from the Canadian Soil Information System Eco-district climate database (CanSIS, 1997) (http://sis.agr.gc.ca/cansis/nsdb/ecostrat/district/climate.html), Farm Environmental Management Survey (FEMS) (Statistics Canada, 2001–2006), Livestock Farm Practice Survey (LFPS) (Statistics Canada, 2007), and Canadian Digital Elevation Data base (CDED) (Centre for Topographic Information et al., 2006) (http://www.geobase.ca/geobase/en/partners/index.html).

Methodology

- ***Crack flow (CF)***

Crack flow is the preferential movement along continuous cracks through an unsaturated soil matrix (Dadfar et al., 2010a). Cracking occurs when soils with significant clay content are drying (Hendrickx and Flury, 2001) and when soil water is evenly distributed. Several factors influence the occurrence and severity of CF. (1) Cracks have to form; ten drying days are usually sufficient for cracks to grow large enough to affect the transport of contaminants. Once the cracks are formed, (2) runoff must occur at the soil surface to penetrate the cracks. (3) Tile drainage, by increasing the heterogeneity of water distribution, increases crack formation. (4) Crops, due to their heterogeneous water extraction, also increase crack formation. Taproots and large roots (e.g., trees), have a greater impact on crack formation. The likelihood of CF occurrence is calculated with equation 3.9:

$$\text{CF} = \frac{\text{Text} * \left[\frac{\sum_{i=1}^{n} \left(\sum_{j=1}^{9} \left[\frac{\sum_{i=1}^{n} (\text{CFE} * \text{Area})_i}{\sum_{i=1}^{n} (\text{Area})_i} * \text{CropArea} \right]_j \div \sum_{j=1}^{9} (\text{CropArea})_j \right)}{n} + \frac{\text{TDrained}}{\text{AGRAREA}} + \frac{\text{RFC}}{\text{TFAREA}} \right]}{10} \qquad (3.9)$$

where:

Text (0-1) is the normalized depth (thickness of three uppermost layers, representing 5%, 7.5%, and 12% of the rooting depth) and surface area weighted average clay content (%) of soil types found in each agricultural SLC (Text=1 when %clay ≥40%; Text=% clay*0.025 when %clay <40%);

i indexes the years used for calculating the likely number of crack flow event(s) occurring in a year (based on 5 years of weather data between Census years);

j indexes the crop types;

CFE is the likely number of crack flow event(s) occurring in a year in each soil type and each crop type, calculated by the VSMB model;

Area and **CropArea** are the areas of soil type (%) and crop type (ha) in a SLC polygon, respectively. The second term in equation 3.9 ranges between 0 and 15 (numbers greater than 15 are set to 15);

TDrained is the total area of till-drained land (ha);

AGRAREA is the total area (ha) of agricultural land in a SLC polygon;

RFC is the summed area (ha) of crops with roots favouring crack formation (alfalfa, buckwheat, corn for grain, corn for silage, forage seed*0.5, oilseeds, other field crops*0.5, pulses or legumes, soybean, sugar beets, tobacco, nursery products*0.39, tree fruit, grapes, berries, Christmas trees, and maple trees/163). On average, there are 163 taps per hectare of maple trees (Chapeski, 2005);

TFAREA is total farm area (ha) in a SLC polygon which is the sum area of hay and field crops, vegetables, nursery products, fruits, berries and nuts, Christmas trees, maple trees, summer fallow land, tame or seeded pasture, and natural land for pasture reported in Census of Agriculture;

CF ranges between 0 and 1 (values higher than 1 were set to 1).

- ***Burrow flow (BF)***

Burrow flow is the preferential movement occurring along animal burrows through an unsaturated soil matrix (Zehe and Flühler, 2001) when runoff occurs. Deep vertical burrows, such as those made by the anecic earthworm *Lumbricus terrestris* L. (Whalen and Fox, 2007), are reported to be the most effective burrow type for transporting contaminants (Stehouwer et al., 1993). The following calculations are based on the population of earthworms in Canada (Dadfar et al., 2010b). Earthworm populations depend on several factors including climate, soil properties, and anthropogenic activity. These components are integrated in the calculations (Equation 3.10) of BF as:

$$BF = \frac{(\text{Precip} + \text{Temp})}{2} * \frac{\sum_{i=1}^{n}\left(\text{Area.}\frac{(\text{ORGC\_N} + \text{C\_N} + \text{SI\_N})}{3}\right)_i}{100} * \frac{\left(\frac{\sum_{j=1}^{7}\left[\sum_{k=1}^{l}(\text{CROP})_k * \text{CRF}\right]_j}{\text{TFAREA}} + \frac{\sum_{p=1}^{5}\left[\sum_{q=1}^{m}(\text{TILLAGE})_q * \text{TMR}\right]_p}{\text{TFAREA}} + \frac{(\text{MANUR} + 0.2\text{NONMANUR})}{\text{TFAREA}}\right)}{3} \tag{3.10}$$

where:

Precip and **Temp** are climatic data; precipitation and temperature, respectively. The climatic conditions of the Quebec/Windsor corridor are considered optimal for *L. Terrestris* in Canada (personal communication: C. A. Fox, October 3-4, 2007);

Precip and **Temp** were set as:

Precip = 0 if TotAnnualPrecip≤500 mm
= (0.02*TotAnnualPrecip)-10 if 500<TotAnnualPrecip<550 mm
= 1 if TotAnnualPrecip≥550 mm

Temp = 0 if 5°C growing degree days (GDD5)≤1250
= (0.00667*GDD5)-8.33 if 1250<GDD5<1400
= 1 if GDD5≥1400

SoilPTL (second term in Equation 3.10) is the potential of a soil to support *L. Terrestris*. This term requires a soil depth of at least 75 cm, the absence of a restricting layer, a pH between 4 and 8, and will be higher with higher organic carbon, total silt, and total clay contents. In the calculation of SoilPTL:

- **i** indexes the number of soil types in a SLC;
- **Area** is the percent of SLC polygons occupied by a soil type;
- **ORGC_N** is the normalized depth weighted mean organic carbon content (ORGCARB) in a 0–75 cm set as:

  ORGC_N = 0.2*ORGCARB if ORGCARB<5
  = 1 if ORGCARB≥5;
- **C_N** is the normalized depth weighted mean total clay content (TCLAY) in a 0–75 cm set as:

  C_N = 0 if TCLAY<5
  = (0.04*TCLAY)-0.2 if 5≤TCLAY<30
  = 1 if TCLAY=30
  = (-0.0143*TCLAY)+1.4286 if 30<TCLAY<100;
- **SI_N** is the normalized depth weighted mean total silt content (TSILT) in a 0–75 cm set as:

  SI_N = 0 if TSILT <5
  = (0.0286*TSILT)-0.1429 if 5≤TSILT<40
  = 1 if TSILT=40
  = (-0.0167*TSILT)+1.6667 if 40<TSILT<100.

Anthropogenic factors (last term in Equation 3.10) include crop factors for burrow, tillage management, and supplemental food sources, such as manure application;

- **j** indexes the number of crop classes;
- **k** indexes the number of crops in each class;
- **CROP** represents the area (ha) of crops in production in a SLC polygon as reported in the Census of Agriculture (CoA-1981, 1986, 1991, 1996, and 2001);
- **CRF** represents the rating factor for each crop class;
- **TFAREA** represents the total farm area (ha) in a SLC polygon (defined in CF);
- **p** represents the number of tillage management classes, **q** is the number of tillage systems in each class;
- **TILLAGE** represents the area (ha) under each tillage systems in a SLC polygon;
- **TMR** represents the rating factor used for each tillage management class;
- **TFAREA** represents the total farm area (ha) in a SLC polygon (defined in CF);
- **MANUR** and **NONMANUR** represent the surface area (ha) of agricultural land in a SLC polygon with and without manure application, respectively;
- **TFAREA** represents the total farm area (ha) in a SLC polygon (defined in CF);
- **BF** ranges between 0 and 1.

- ***Finger flow (FF)***

Finger flow occurs when infiltrating water accumulates at the interface between two contrasting soil layers, usually in sandy soil with a coarse textured horizon underlying a fine textured horizon. The water breaks into the subjacent layer through fingers or preferential flow paths rather than uniformly through the entire layer (Rezanezhad et al., 2006). Coarse fragments, such as stones, are considered to increase FF (Baker and Hillel, 1990):

$$\mathrm{FF} = \frac{\sum_{i=1}^{n}\left[\dfrac{\sum_{k=1}^{m}\left[(\mathrm{y}+\mathrm{NCOFRAG}).\mathrm{L}\right]_k}{\sum_{k=1}^{m}\mathrm{L}_k} * \mathrm{Area}\right]_i}{\sum_{i=1}^{n}(\mathrm{Area})_i} \tag{3.11}$$

where:

NCOFRAG is the normalized coarse fragments content (zero when y is zero);

L is the layer depth;

Area is the percent area of a SLC polygon occupied by a soil type;

i indexes the number of soil types in a SLC;

k indexes the number of layers in a soil profile;

y is a weighting factor of 0.8 or 0, for layers with (≥70% sand) and without (<70% sand), respectively;

FF ranges between 0 and 1.

- ***Lateral flow (LF)***

Lateral flow occurs when infiltrating water moves laterally along a cemented-indurated horizon, i.e., bedrock (Mcdonnell, 1990), or along lateral roots. Critical properties influencing LF are the presence of trees, a restricting layer, the depth to a restricting layer, and slope gradient. The likelihood of LF (Equation 3.12) is calculated as:

$$LF = Slope * \left[\frac{\sum_{i=1}^{n} \left(RESTER\_TYPE_{wf} \ . \ DEPTH_{wf} \ .Area \right)_i}{\sum_{i=1}^{n} (Area)_i} + \frac{TREES}{TFAREA} \right] \qquad (3.12)$$

where:

Slope is the percent rise in a SLC (slope=1 if percent rise≥10%; slope=percent rise*0.1 if percent rise<10%). The Canadian Digital Elevation Data (CDED) at scale of 1:50,000 were used to determine slope by calculating percent rise (Centre for Topographic Information et al., 2006; ESRI, 2007). The percent rise was then aggregated to SLC using the mean percent rise found intersecting the SLC polygon (area weighted average procedure when polygons intersect on more than one mapsheet);

i indexes the number of soil types in a SLC polygon;

$RESTER\_TYPE_{wf}$ is a factor used for defining a soil with (1) or without (0) a root restricting layer;

$DEPTH_{wf}$ is factors used for depth to restricting layer;

Area is percent area of SLC polygon occupied by a soil type;

TREES (ha) is sum area of nursery products (TNURSRY × 0.2), tree fruit **(**FRTTREE), grapes total area (FRTGRP), Christmas trees (XMSTREE), and maple trees (MAPLET/163 taps ha^{-1});

TFAREA is the total farm area (ha) in a SLC polygon (defined in CF);

LF ranges between 0 and 1.

General Assumptions and Limitations

- ***Crack flow***
  - Assumptions: A minimum of 10 consecutive water deficit days followed by a net daily rainfall (Net daily rainfall = total daily rainfall – interception, i.e., infiltration) of at least 10 mm are assumed necessary for CF. For forage seed and other field crops, 50% of area, and for nursery products, 39% of area, is assumed to be crops with roots favouring crack formation.
  - Limitations: The number of days for crack formation is not equal for different soils, crops, and weather conditions, but it is based on expert knowledge. The rainfall depth necessary to form runoff depends on initial water content and soil hydraulic properties; these factors are not

sufficiently detailed in the database and are based on expert knowledge. The correlation between crop and soil position in a SLC is unknown, thus decreasing the precision of CFE. There is no national database on tile drainage (TD) and the exact distribution of TD over the SLC is unknown.

- ***Burrow flow***
  - Assumptions: Total annual precipitation of ≥550 mm, 5°C growing degree days of ≥ 1400, soil pH in the range of 4.0 to 8.0, ≥75 cm soil depth, and crop residue left on soil surface are assumed optimal conditions for earthworm survival. They are based on literature and expert knowledge.
  - Limitations: Calculations are based on optimal conditions for *Lumbricus terrestris* L. Other earthworm species that make vertical burrows may require different environmental conditions for optimal growth.

- ***Finger flow***
  - Assumptions: Finger flow develops in a sandy horizon with a total sand content ≥70% anywhere in the soil profile (except on the soil surface) when it is overlaid by a finer layer.
  - Limitations: The threshold value for a sandy horizon (≥70% total sand content), the weighting factors for sand layer (0.8), and coarse fragments (maximum 0.2) are based on expert knowledge.

- ***Lateral flow***
  - Assumptions: It is assumed that the cemented-indurated horizon follows the same slope as the soil surface. For nursery products, 20% of area is assumed to be trees.
  - Limitations: The weighting factor for depth is based on expert knowledge.

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