AGRI-ENVIRONMENTAL INDICATOR PROJECT

Agriculture and Agri-Food Canada

REPORT NO. 23

SOIL DEGRADATION RISK INDICATOR: SOIL COMPACTION COMPONENT

Technical Report: Feasibility Study on the Development and Testing of Agri-Environmental Indicators of Soil Compaction Risk (Eastern Canada)

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PREFACE

The Agri-Environmental Indicator (AEI) Project of Agriculture and Agri-Food Canada (AAFC) was initiated in 1993 in response to recommendations made by several agencies, organizations and special studies. The overall objective of the project is to develop and provide information to help integrate environmental considerations into decision-making processes of the agri-food sector.

The project aims to develop a core set of regionally-sensitive national indicators that build on and enhance the information base currently available on environmental conditions and trends related to primary agriculture in Canada. The feasibility study on the soil compaction risk component of the Soil Degradation Risk indicator is an important part of the agri-environmental indicator set. Indicators are also being developed for other aspects of soil degradation risk and in relation to issues of water quality, agroecosystem biodiversity, farm resource management, agricultural greenhouse gases and agricultural production efficiency.

Research results in the form of discussion papers, scientific articles and progress reports are released as they become available. A comprehensive report is planned for fiscal-year 1998-1999 which will include data from the 1996 Statistics Canada Census of Agriculture.

Comments and questions on this paper as well as about the tabular data created and used in the feasibility study on the soil compaction component should be addressed to:

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1. Introduction

Surveys commissioned by Agriculture and Agri-Food Canada (AAFC) have shown that agricultural soil compaction is the soil and water conservation problem identified most frequently by corn producers in southern Ontario as a concern on their farms (Deloitte and Touche, 1991). It has further been estimated that 50 to 70 percent of the fine-textured soils of southwestern Ontario have been adversely affected by soil compaction, with ¾ of this affected land area rated as moderately compacted and ¼ as severely compacted (Can-Ag Enterprises, 1988). Many parts of the Maritime provinces also have naturally compacted subsoils (Carter et al., 1996). Soil compaction caused by the use of heavy machinery (Hakansson et al., 1987) may be costing the Ontario agricultural economy $21 M annually and the Quebec economy $100M (Science Council of Canada, 1986).

Recent advancements in the field of pedotechnology make it possible to estimate the maximum compactive stresses which have acted upon a soil with minimal soil inventory data (McBride and Joosse, 1996). Using generalized soil inventory data at a national scale, such as the Soil Landscapes of Canada (SLC) database, it is possible to assess the present state of overconsolidation of soils in many regions of eastern Canada.

1.1 Soil Processes and Pedotransfer Functions

Soil structural degradation caused by wheel traffic from heavy agricultural vehicles can take on many forms. Apart from soil compaction, other processes include plastic deformation and shear failure. Some of these other soil processes are often mistakenly referred to as soil compaction. This term, in fact, only refers to the process of increasing the dry bulk density of an unsaturated soil by packing the primary soil particles and aggregates more closely together with a reduction in the volume of air in soil pores. Many soil compaction models are currently available, and the better examples include all of the elements necessary to simulate soil mechanical behaviour under a range of initial conditions (Jakobsen and Dexter, 1989; Plouffe et al., 1994). Many of these models, however, have very extensive input data requirements which makes them difficult to apply to regional, provincial or national studies of soil compaction risk (Bober et al., 1996).

Generalized soil inventory information exists for most of the settled part of Ontario, but the development of useful soil survey interpretation schemes (or "pedotransfer functions" [PTFs]) has generally lagged far behind. A recent study carried out in southern Ontario, however, investigated the usefulness of the "preconsolidation stress" (σ'_c) in characterizing the pre- and post-traffic structural state of agricultural soils as well as their vulnerability to further loss of total porosity with wheel traffic (Veenhof and McBride, 1996; McBride and Joosse, 1996). In soil mechanics, this empirically-measured variable is defined as the maximum vertical stress that has acted on an overconsolidated (saturated) soil in the past. In unsaturated soils, however, this variable is regarded more commonly as the stress above which soil deformation greatly increases, since many other factors contributing to structural strength come into play such as large effective stresses caused by freezing or drying, the presence of organic and inorganic stabilizing materials, and age-hardening or hard setting behaviour (Kay, 1990). This variable was found to be very useful in establishing the degree of agricultural soil overconsolidation as well as maximum allowable wheel loads to avoid further compression of soils in agricultural fields.

Recent research has corroborated the hypothesis that the compressive behaviour (static, uniaxial) of structured subsoils in Ontario can be predicted reasonably well from the consolidation behaviour of those same soils when in a remoulded (slurried) condition, and hence from their Atterberg consistency limits (McBride and Baumgartner, 1992). As a result, a PTF has been developed that can assist in characterizing the degree of overconsolidation of soils without the need for an extensive and costly soil compression testing program. This simple set of functions estimates the preconsolidation stress from dry bulk densities (void ratios) measured in situ and from other soil properties needed to estimate the normal consolidation line.

Preliminary testing of the PTF has been carried out by assembling the necessary data on soil physical properties for all soil series characterized by O.C.S.R.E. (Ontario Centre for Soil Resource Evaluation) during the course of the last five county-level soil inventory upgrades in southwestern Ontario that meet the minimum data requirements (i.e., 282 horizons from 91 soil profiles [McBride and Joosse, 1996]). Unfortunately, these soil sampling locations were selected more for pedological and taxonomic reasons than for their representativeness of the soil and crop management practices most commonly applied to these soil series/associations. Consequently, the PTF needs to be tested further on more appropriate data sets (e.g., Tillage 2000).

1.2 PTF Calculations

McBride and Joosse (1996) introduced a series of calculations which determine the "minimum possible σ'_c" from the estimated normal compression line (NCL) of a soil. This sequence of equations is presented in Eq. [1] through [7] and comprise the PTF. To express the NCL in $e(\log\sigma')$ co-ordinates, Eq. [1] to [3] are used to convert the in situ dry bulk density of a soil, as well as its liquid and plastic limits, into void ratios. Field dry bulk densities are transformed with

$$e_o = \frac{\rho_p}{\rho_b} - 1 \qquad [1]$$

where e_o is the in situ void ratio, ρ_p is the in situ dry bulk density (Mg m^{-3}), and ρ_b is the soil particle density (Mg m^{-3}). Given that Atterberg limits can be measured by slurry consolidation (McBride and Baumgartner, 1992), these test indices can be taken to represent saturated water contents as follows:

$$e_{w_L} = \frac{w_L \cdot \rho_p}{\rho_w} \qquad [2]$$

where e_{wL} and w_L represent the liquid limit expressed as a void ratio and gravimetric soil water content (kg kg^{-1}), respectively, and ρ_w is the density of water (Mg m^{-3}) and

$$e_{w_P} = \frac{w_P \cdot \rho_p}{\rho_w} \qquad [3]$$

where e_{wp} and w_P represent the plastic limit expressed as a void ratio and a gravimetric soil water content (kg kg^{-1}), respectively.

The effective stresses at the liquid limit (σ'_{wL}) and plastic limit (σ'_{wP}) were estimated with Eq. [4] and a constant 420 kPa, respectively (McBride and Baumgartner, 1992):

$$\sigma'_{wL} = 26.6 - (32.1 \log \mathrm{OC}) \qquad [4]$$

where OC is the organic C content (%kg kg^{-1}). Equations [5] and [6] were used to compute the NCL slope (C_c^*) and the void ratio at unit stress (e^*_{1kPa}) for a given soil. This is done by using the two known points, (e_{wL}, σ'_{wL}) and (e_{wP}, σ'_{wP}), and assuming a linear function in $e(\log\sigma')$ co-ordinates as follows:

$$C_c^* = \frac{e_{wL} - e_{wP}}{\log\left(\dfrac{\sigma'_{wP}}{\sigma'_{wL}}\right)} \qquad [5]$$

$$e^*_{1kPa} = e^*_{wP} - (2.623\ C_c^*) \qquad [6]$$

The equation for the NCL is then

$$e = e^*_{1kPa} - (C_c^* \log\sigma') \qquad [7]$$

1.3 Soil Landscapes of Canada (SLC)

Where all of the necessary polygon attributes are available, this PTF can be used to estimate σ'_c for large areas using soil data mapped under the Soil Landscapes of Canada (scale 1:1,000,000). The minimum attributes required to apply the PTF (i.e., organic C content, dry bulk density, soil texture) at a national scale are contained in the SLC database (Version 2.1). The SLC database has been compiled by Agriculture and Agri-Food Canada (AAFC) as a series of GIS coverages, at the 1:1 million scale, showing the dominant soil and land characteristics for all of Canada as derived from existing soil survey maps. A soil landscape is defined as the "full array of attributes that describe a distinct type of soil and its associated landscape, such as surface form, slope, water table depth, permafrost and lakes" (Shields et al., 1991, p. 5). A polygon identified in a SLC GIS coverage may consist of one or more distinct soil landscapes called "components". Each component is characterized with regard to its percent coverage within the polygon and ranked (i.e., assigned a value of 1 to n with 1 having the highest percent coverage within the polygon) with respect to the other components within the polygon. The components are further characterized with respect to the kind of surface material, vegetation cover and/or land use, parent material mode of deposition, coarse fragment content of the control section, rooting depth, drainage class, soil development class, parent material calcareousness class, local surface form, and slope gradient. However, the location of a component within a SLC polygon is not defined. Note that the term "soil" and "soil component" are used interchangeably hereafter.

Each component is linked to a separate table named LYR (or "layer") which describes the properties of the associated soil layers. There can be up to three layers in a given component with the following definitions.

1- the surface organic layer of mineral or organic soils.

2- the subsurface organic layer of organic soils; or the upper mineral layer of mineral soils.

3- the subsurface mineral layer of mineral and organic soils.

Only mineral soils are being considered in this study. Consequently, these designations can be simplified to the descriptions of layers 2 and 3 above which pertain to mineral soils only. Each layer is characterized in terms of textural class, dry bulk density and organic C content. These data provide the required input data for the PTF.

1.4 Objectives

The primary objective of this feasibility study was to develop and test criteria for provincial-level soil compaction risk assessment using the Soil Landscapes of Canada database, where the available soil data are very limited (e.g., soil texture, organic C content and dry bulk density). The specific objectives are:

1. to determine the present state of overconsolidation (due to natural and/or anthropogenic causes) in agricultural soils in predefined areas of eastern Canada,
2. to estimate the maximum allowable wheel loadings on these soils before significant additional compaction will occur,
3. to evaluate the risk of further soil compaction damage based on the findings under Objectives 1 and 2, in conjunction with land use patterns (1991 Census of Agriculture) contained in the Soil Landscapes of Canada database.

In meeting these objectives a series of maps would be generated depicting the preconsolidation stress estimates for Ontario and the Atlantic provinces. Maps would also be generated identifying those areas likely to experience improvements in soil structure and those under the highest risk of further soil compaction damage. In addition, it would be possible to provide an evaluation of the suitability of the SLC database for making assessments of the state of overconsolidation of agricultural soils at a provincial scale.

2. Methods

This research was carried out in several stages: data acquisition, estimation of missing soil properties, application of inclusion criteria to the SLC database, application of the PTF and data analysis. These stages are outlined below.

2.1 Data Acquisition

Arc/Info coverages from the SLC database were obtained for Ontario and the Atlantic provinces from the CanSIS web page at http://res.agr.ca/CANSIS/. Coverages for Quebec were not included in this feasibility study due to the predominance of clay minerals other than clay mica (illite) in the soils of the agricultural regions in this province. Data were downloaded as compressed Arc/Info export coverages and imported into ArcView 2.0. This created ArcView directories and themes for each province from which the component and layer table data were retrieved.

The 1991 Census of Agriculture data were then acquired from Agriculture and Agri-Food Canada (Ontario Land Resource Unit, Guelph) in dbf format. These data were derived from the full 1991 Census of Agriculture (Statistics Canada) and provide agricultural land use (cropping pattern) summaries for each of the SLC polygons found in the agricultural areas.

2.2 Soil Property Estimations

The SLC data acquired from the web site included only the minimum essential properties (i.e., soil texture, dry bulk density, and organic C content) required to apply the PTF.

From these properties the remaining soil characteristics could be estimated including Atterberg limits, particle density, and actual clay content.

Atterberg limits were estimated using equations developed by Watson (1996). These equations were developed from the same dataset assembled by McBride and Joosse (1996) to develop the pedotransfer function (i.e., five counties in southwestern Ontario). Watson (1996) organized the data into two groups based on measured organic C content (either 0 or > 0 %kgkg^{-1}) and developed separate equations for each group. Table 1 summarizes the derived equation coefficients for both Atterberg limits.

Table 1. Atterberg limit regression results.

Atterberg Limit	Organic C Content Group	n	Coefficients		Intercept	r^2	Standard Error of Estimate
			Clay (%kg·kg^{-1})	OC† (%kg·kg^{-1})			
Liquid Limit	> 0	220	0.54	3.20	16.50	0.779 **	5.50
	= 0	80	0.57		18.14	0.788 **	5.41
Plastic Limit	> 0	220	0.10	3.67	15.00	0.614 **	3.87
	= 0	80	0.17		12.84	0.596 **	1.91

† Organic C content.

** Significant at the 0.01 probability level.

Particle density (ρ_p)was estimated using the following equation:

$$\rho_P = 2.659 - (OC \cdot 0.045)$$

where OC is the organic C content (%kg·kg^{-1}). This is an unpublished equation, also based on the same dataset used by McBride and Joosse (1996).

Finally, clay content was estimated from the textural classes assigned in the SLC database. This was accomplished by determining the mid-point for the range of clay contents possible for each textural class reported. Table 2 summarizes the clay content estimates by textural class.

Table 2. Clay content estimate by textural class.

Code	Textural Class	Estimated Clay Content (%kg·kg^{-1})
CBS	Cobbly sand	5
VGS	Very gravelly sand	5
GS	Gravelly sand	5
S	Sand	5
CS	Coarse sand	5
FS	Fine sand	5
VS	Very fine sand	5
LFS	Loamy fine sand	7
LVFS	Loamy very fine sand	7
CBLS	Cobbly loamy sand	7
VGLS	Very gravelly loamy sand	7
GLS	Gravelly loamy sand	7
LS	Loamy sand	7
CBSL	Cobbly sandy loam	10
VGSL	Very gravelly sandy loam	10
GSL	Gravelly sandy loam	10
SL	Sandy loam	10
GFL	Gravelly fine sandy loam	10
FL	Fine sandy loam	10
CBL	Cobbly loam	17
GL	Gravelly loam	17
L	Loam	17
VL	Very fine sandy loam	10
GSIL	Gravelly silt loam	14
SIL	Silt loam	14
SI	Silt	6
GSCL	Gravelly sandy clay loam	26
SCL	Sandy clay loam	26
VCL	Very fine sandy clay loam	26
CBCL	Cobbly clay loam	34
GCL	Gravelly clay loam	34
CL	Clay loam	34
SICL	Silty clay loam	34
SC	Sandy clay	44
C	Clay	50
GSIC	Gravelly silty clay	50
SIC	Silty clay	50
HC	Heavy clay	70

2.3 Inclusion Criteria

It was necessary to apply certain inclusion criteria to the SLC data. Those criteria are based on the characteristics of the data upon which the PTF was originally developed. Consequently, only those polygon components and component layers described in the SLC database which met those criteria have been included in the data analysis. The criteria are described below.

1. As the PTF is only applicable to mineral soils, the soil layers coded as a "1" (surface organic layer of mineral or organic soils) for the LAYERNO attribute were discarded. The remaining component layers, which were classed as either 2 or 3, were then grouped according to the assigned KINDMAT attribute class. KINDMAT identifies the "kind of soil, rock outcrop or other material at the surface." Only those soil components characterized as mineral (i.e., "SO") were included in the analysis.

2. The PTF is not applicable to soils dominated by clay mineralogy other than clay mica (illite). Thus, soils of marine origin were discarded. This eliminated certain soil components of polygons in eastern Ontario.

3. The equations developed by McBride and Joosse (1996) and Watson (1996) were generated from a dataset with virtually no samples exceeding an organic C content of 5%$\text{kg}\cdot\text{kg}^{-1}$. Therefore, only soils with an organic C content of 5% or less were included in the analysis.

4. The PTF is only applicable to plastic soils. In general, Ontario soils with a clay content of less than about 10 %$\text{kg}\cdot\text{kg}^{-1}$ are nonplastic (McBride and Baumgartner, 1992) and are therefore not appropriate for application of the PTF. Even soils with 10-15% clay are marginally plastic at best, but have been included in the analysis due to the exploratory nature of this study. Soil components with an estimated clay content of less than 10% were discarded (i.e., silts, sands, loamy sands).

2.4 PTF Calculation and Data Analysis

A subset of the SLC database was compiled according to the inclusion criteria described in Section 2.3, and missing data were estimated in accordance with procedures described in Section 2.2. The PTF was applied in Microsoft Excel according to the equations described in Section 1.2.

Soil component and layer data were segregated into several categories for the purpose of analysis. The vegetation cover (VEGET) attribute of the polygons was used to segregate the data into "agricultural" and "non-agricultural" groups. Agricultural polygons included those characterized as 'A' (agricultural crops) and 'G' (improved pasture). Data were further segregated into groups of surface and subsurface soil layers. The attribute LAYERNO was equal to '2' for surface soils and '3' for subsurface soils. Finally, the data were grouped by province.

The data were not normally distributed and a log transformation of the data was found to be necessary to allow for mean separation testing. A Tukey honest significant difference test for unequal sample sizes was used to make inter-provincial comparisons of the means using Statistica (Statsoft, 1995). While the log transformed data were used to determine significant differences between provinces, the results are reported as non-transformed mean values. The σ'_c values for the dominant soil components of the agricultural areas were mapped for each province in ArcView 2.0 by categorizing them in ranges of 0 to 20 kPa, 20 to 100 kPa, and greater than 100 kPa. It is recognized by the authors that mapping only the dominant component in each polygon can potentially be misleading. However, this method provides a means, within the limitations of the SLC data, of representing dominant trends.

The 1991 Census of Agriculture data were then used to identify the areas which are most likely to experience a change in soil structural condition or state of overconsolidation as a result of general agricultural land use patterns (Kay, 1990). This was determined by reviewing the crop categories and judging which were most likely to lead to improvements in soil structure and which were most likely to have a detrimental effect on soil structure (i.e., cause further soil compaction damage). The alfalfa, hay, improved pasture and unimproved pasture crop categories were judged as being conducive to improving soil structure and ameliorating compacted soil layers over time. Conversely, grain corn, vegetable crops, and potatoes/beets and were judged as being potentially damaging to the soil structural condition and most likely to create significantly compacted soil layers. The fractions of the total cropland area associated with these two categories of agricultural land uses were summed individually for each polygon. Frequency distributions were computed and the polygons with the highest percentage of their total cropland under each of the two categories of land use were identified. The land areas most likely to experience improvements in soil structure and a lessening in the degree of overconsolidation were identified as those polygons where at least $^1/_3$ of the total cropped area was under "soil structure replenishing" land uses and the σ'_c value of the dominant soil component was relatively high (i.e., greater than 100 kPa). The land areas most at risk of further soil compaction and structural deterioration were identified as those polygons where at least $^1/_5$ of the total cropped area was under "soil structure depleting" land uses and the σ'_c value of the dominant soil component was relatively low (i.e., less than 100 kPa). These polygons were identified and mapped using ArcView 2.0.

A lower threshold ($^1/_5$) was used for the annual row crop group due in part to the frequency distribution, which only showed a very small proportion of polygons at the $^1/_3$ or greater level. Furthermore, the SLC land use data did not differentiate between soybeans and other oilseed crops (e.g., canola). If this distinction had been possible, soybeans would have been included in the "soil structure depleting" category of land uses and a threshold of $^1/_3$ would likely have been appropriate.

Finally, a comparative evaluation was made between the PTF results obtained using the SLC database and those obtained from much more detailed soil survey datasets. The results reported by McBride and Joosse (1996) for the General Linear Model analysis of σ'_c estimates for a five-county dataset in southwestern Ontario were used for this comparison. A SLC coverage for this five-county region was created using ArcInfo. A direct comparison between the results was not possible because of i) variation in the soil texture data available (i.e., textural classes vs. particle-size classes), and ii) the lack of differentiation between B and C subsurface horizons in the SLC database. However, approximate comparisons were possible.

A request was submitted to CanSIS (Ottawa) for additional detailed soil survey datasets for New Brunswick and Nova Scotia so that a similar comparison could be made for selected areas in the Maritime provinces. These data were not received in time for inclusion in this report.

3. Results and Discussion

3.1 Preconsolidation Stress Estimates (σ'_c)

Tables 3 and 4 summarize the results of the preconsolidation stress estimates (σ'_c) and analysis of surface and subsurface layers for all soil components which met the inclusion criteria. These tables report the antilog of the mean log σ'_c values for each province, and for all five provinces combined, grouped by surface and subsurface soil components and by agricultural and non-agricultural land use classes. Significant differences ($P < 0.05$) between means by column are also reported along with the sample sizes (n). Statistically significant differences between the major land use groups within a table (i.e., agricultural vs. non-agricultural) will be discussed in the following sections, but the mean separation statistics are not presented in Tables 3 and 4. Table 5 summarizes the mean values of clay content, dry bulk density, and organic C content (i.e., the inputs for the PTF) for the same dataset.

Maps 1 to 4 present the estimates of σ'_c values calculated for the subsurface layers of the dominant soil components for all polygons in each of the provinces which met the inclusion criteria and where the dominant soil component is categorized as agricultural. As described in Section 2.4, the σ'_c values are categorized for these maps as 0 to 20 kPa, 20 to 100 kPa and greater than 100 kPa. The 0 to 20 kPa category is based on a partitioning of sample points observed from a frequency distribution of the data. The greater than 100 kPa category corresponds to the stress level above which soils are considered to be overconsolidated. Maps 1 to 4 satisfy objectives 1 and 2 by showing i) the spatial distribution of the degree to which the soils in the agricultural areas are overconsolidated, and ii) the maximum allowable wheel loading that can be sustained by the soils of those areas before significant soil compaction is likely to occur.

Table 3. Analysis results of σ'_c estimates[§] for surface soil components.

	Agricultural		Non-Agricultural	
Region[†]	mean (kPa)[‡]	(n)	mean (kPa)[‡]	(n)
All Five Provinces	2.68	(699)	5.96	(225)
ON	6.39 a	(401)	11.21 b	(140)
NF	-	(0)	526.32 a	(11)
NS	0.85 b	(208)	0.55 c	(30)
PE	0.55 b	(39)	-	(0)
NB	1.06 b	(51)	1.32 c	(44)

[†] ON = Ontario; NF = Newfoundland; NS = Nova Scotia; PE = Prince Edward Island; NB = New Brunswick.

[‡] Treatment means by column (excluding "all five provinces") followed by different lower case letters are significantly different at the 95% confidence level ($P<0.05$).

[§] All reported means are antilogs of mean $\log\sigma'_c$ values.

Table 4. Analysis of results of σ'_c estimates[§] for subsurface soil components.

	Agricultural		Non-Agricultural	
Region[†]	mean (kPa)[‡]	(n)	mean (kPa)[‡]	(n)
All Five Provinces	29.03	(615)	7.73	(2228)
ON	28.99	(357)	5.61 ab	(136)
NF	-	(0)	5.29 b	(323)
NS	29.12	(181)	8.43 a	(808)
PE	20.68	(29)	126.87 ab	(4)
NB	35.65	(48)	8.46 a	(957)

[†] ON = Ontario; NF = Newfoundland; NS = Nova Scotia; PE = Prince Edward Island; NB = New Brunswick.

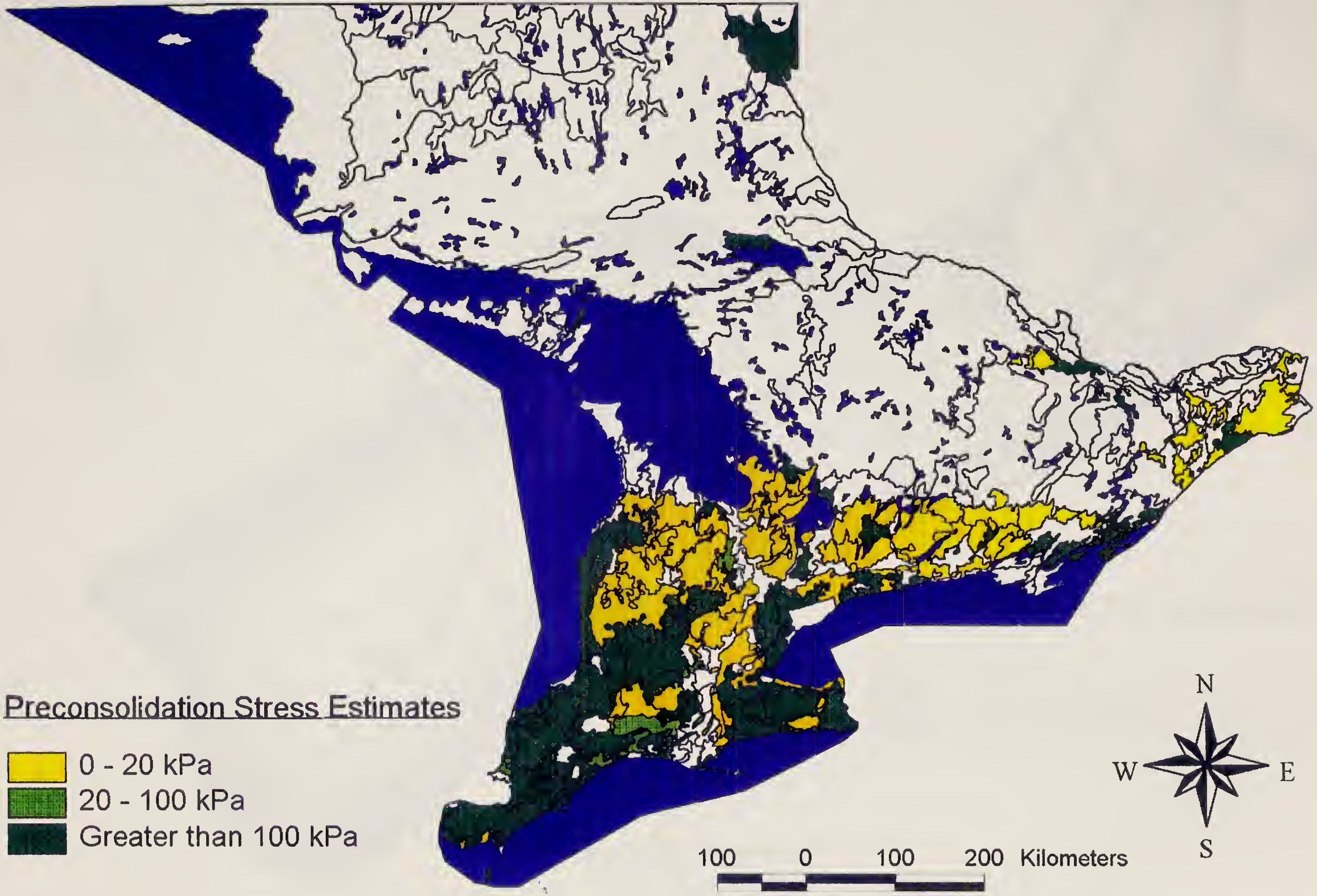
[‡] Treatment means by column (excluding "all five provinces") followed by different lower case letters are significantly different at the 95% confidence level ($P<0.05$).

[§] All reported means are antilogs of mean $\log\sigma'_c$ values.

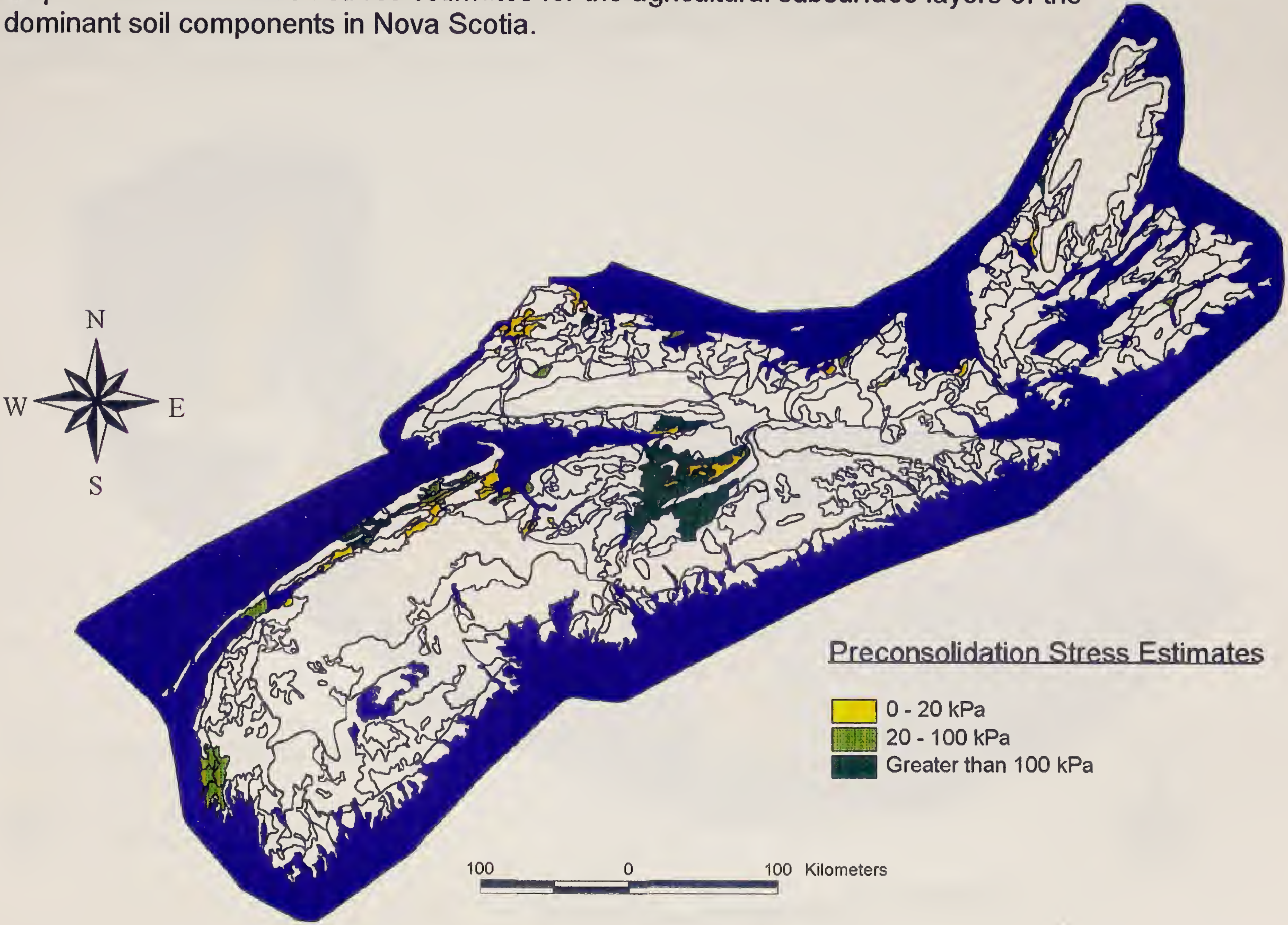
Table 5. Mean values of inputs into PTF.

	Grouping	n	Clay Content ($\%kg \cdot kg^{-1}$)	Dry Bulk Density ($g \cdot cm^{-3}$)	Organic C Content ($\%kg \cdot kg^{-1}$)
Non-Agricultural Surface Soil Components	NB	44	16.73	1.11	3.73
	NF	11	10.00	1.43	3.80
	NS	30	15.97	1.14	1.46
	ON	140	17.14	1.35	2.44
	PE	0	--	--	--
	All Five Provinces	225	16.55	1.28	1.89
Non-Agricultural Subsurface Soil Components	NB	957	16.10	1.44	1.20
	NF	136	12.44	1.43	1.28
	NS	323	13.25	1.48	0.60
	ON	136	19.92	1.40	0.41
	PE	4	13.75	1.71	0.25
	All Five Provinces	2228	14.77	1.45	0.94
Agricultural Surface Soil Components	NB	51	15.92	1.19	2.78
	NF	0	--	--	--
	NS	208	14.71	1.27	1.37
	ON	401	23.59	1.31	2.03
	PE	39	10.36	1.22	1.99
	All Five Provinces	699	19.65	1.28	1.89
Agricultural Subsurface Soil Components	NB	48	21.90	1.53	0.73
	NF	0	--	--	--
	NS	181	15.19	1.55	0.33
	ON	357	31.02	1.44	0.36
	PE	29	10.48	1.58	0.66
	All Five Provinces	615	24.68	1.49	0.40

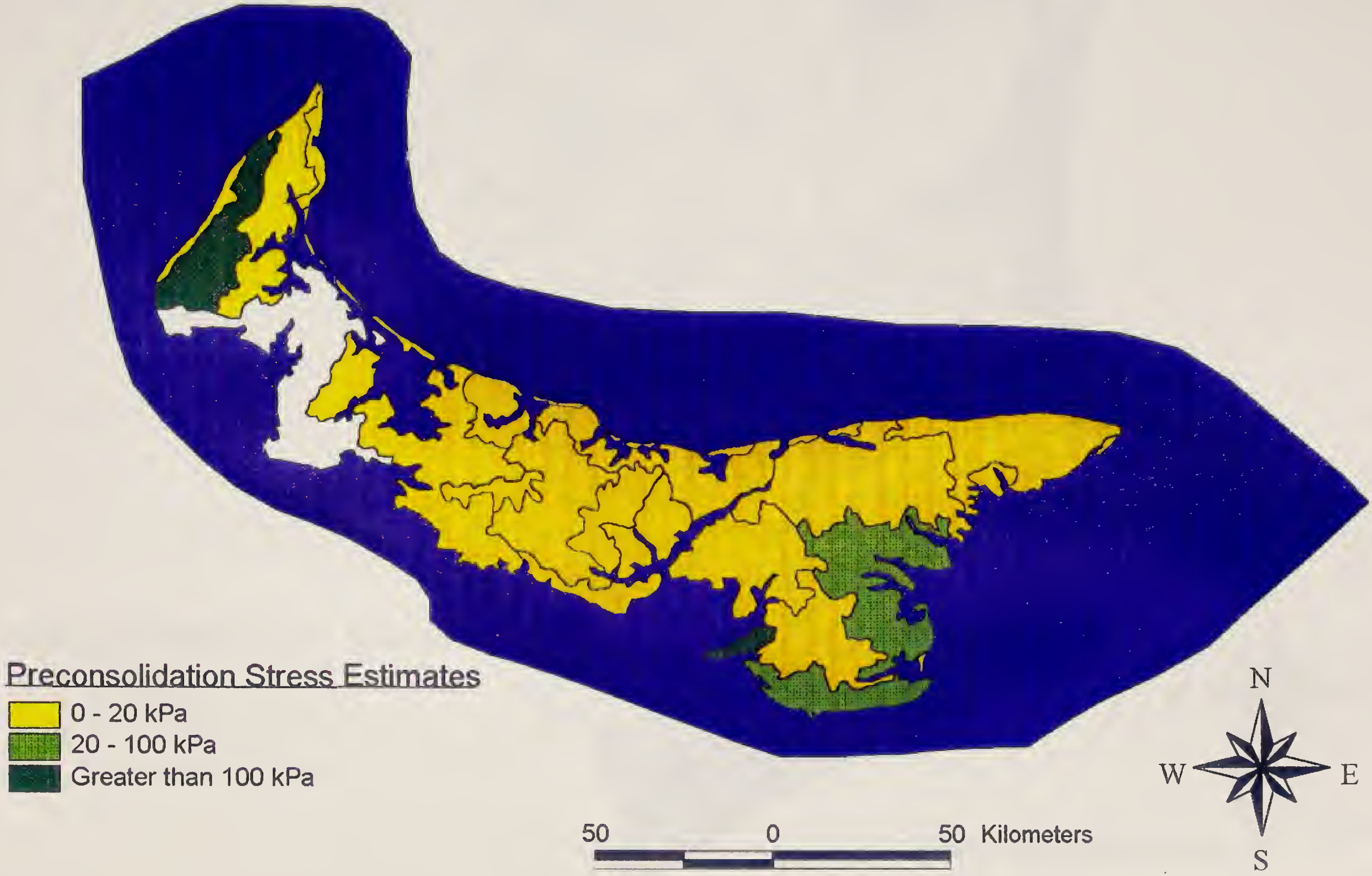
Map 1. Preconsolidation stress estimates for the agricultural subsurface layers of the dominant soil components in the southern half of Ontario.



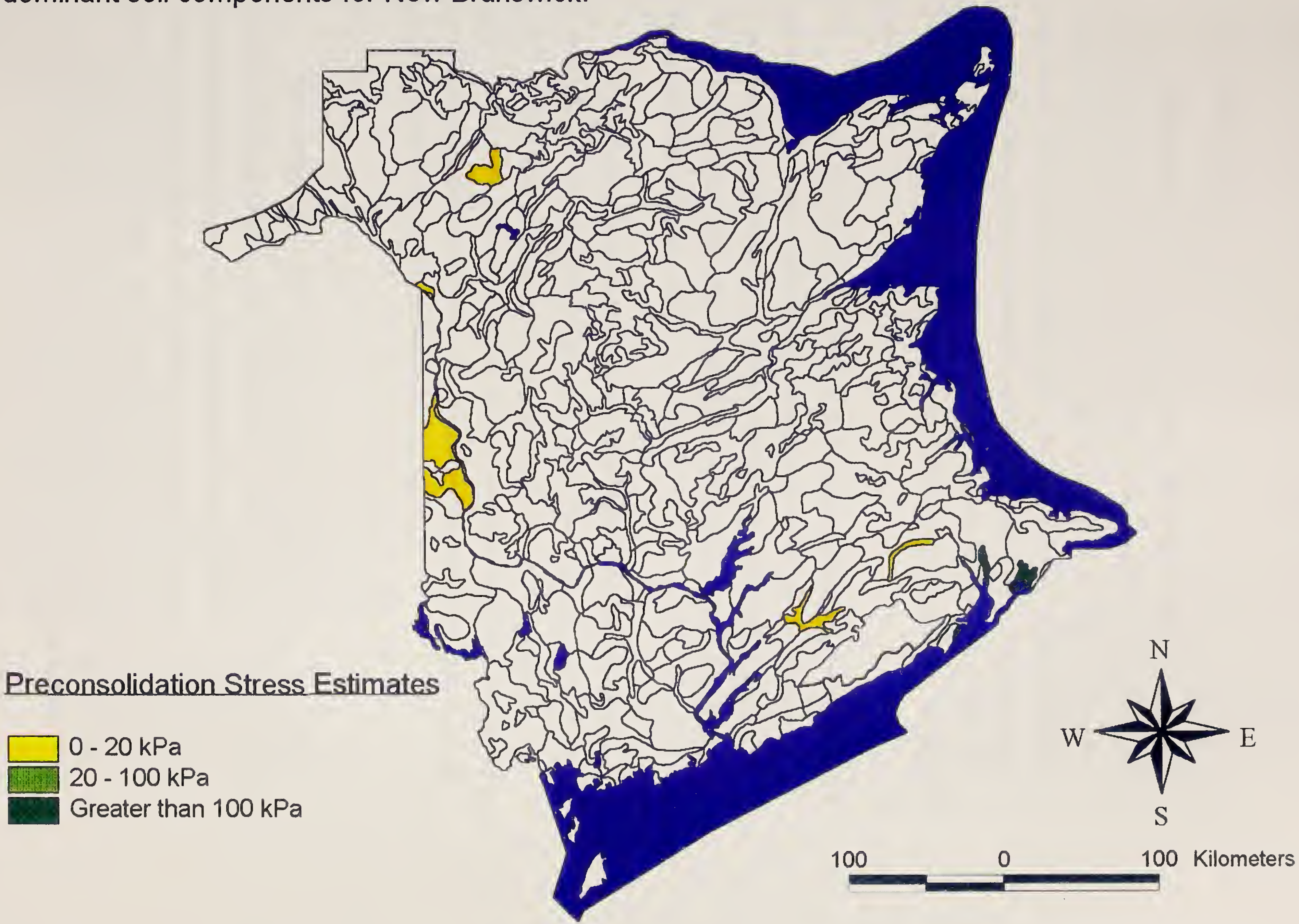
Map 2. Preconsolidation stress estimates for the agricultural subsurface layers of the dominant soil components in Nova Scotia.



Map 3. Preconsolidation stress estimates for the agricultural subsurface layers of the dominant soil components in Prince Edward Island.



Map 4. Preconsolidation stress estimates for the agricultural subsurface layers of the dominant soil components for New Brunswick.



3.1.1 All Five Provinces

The analysis of all soil components associated with polygons classified as agricultural for all five provinces showed a mean σ'_c of 29.0 kPa for the subsurface horizons and a mean σ'_c of 2.7 kPa for the surface horizons. These means are significantly different and follow the expected pattern, where the consolidation state of surface horizons for agricultural soils are influenced by tillage operations (loosened). In the non-agricultural areas, where there is no influence of farm operations, the difference between the surface soil components (mean 6.0 kPa) and the subsurface soil components (mean 7.7 kPa) is less pronounced and not statistically significant.

For subsurface soil components (Table 4), the agricultural soils (mean 29.0 kPa) have a significantly higher mean σ'_c than the non-agricultural soils (mean 7.7 kPa). This is the expected trend since the former group of soils would have been subjected to the compactive effects of agricultural vehicle traffic. Pressure waves are known to reach considerable depths into the subsoil (Plouffe et al., 1994).

The agricultural surface soil components (Table 3) also have a mean σ'_c that is significantly lower than that of the non-agricultural surface soil components. It is likely that the effects of tillage on loosening agricultural topsoils is largely responsible for the lower agricultural mean. A closer look at the data, however, also reveals that it is soil components from Ontario and Newfoundland which are responsible for the elevated non-agricultural mean. These trends will be discussed further in Sections 3.1.2 and 3.1.3.

3.1.2 Ontario

Map 1 shows the spatial distribution of the preconsolidation stress estimates for the subsurface horizons of the dominant soil components in Ontario. Note that polygons that have not been assigned a σ'_c value have been excluded from the analysis for one or more of the reasons outlined in Section 2.3. Unfortunately, mapping only the dominant soil components does not allow the presentation of the PTF findings for the sub-dominant components, but it is not practicable to create maps for all sub-dominant components in each polygon. Mapping only the dominant soil components does, however, allow for a quick visual assessment of the trends in the data. All tabular data created and used in this study are available in a MS Excel spreadsheet format, and can be obtained from Dr. G. Wall (AAFC, Guelph, ON).

The analysis of the estimated σ'_c values for all soil components in agricultural areas of Ontario shows that the surface soils (mean 6.4 kPa) are significantly less consolidated than the subsurface soils (mean 29.0 kPa). In addition, the agricultural subsurface soils are significantly more consolidated than the non-agricultural subsurface soils (mean 5.6 kPa). The non-agricultural surface soil components (mean 11.2 kPa), however, are more consolidated than the non-agricultural subsurface soil components (mean 5.6 kPa) and the agricultural surface soil components (mean 6.4 kPa), although the latter contrast is not significant. This former finding was difficult to rationalize, but a closer look at the data revealed a large group of non-agricultural surface soil components (n=34) with relatively low plasticity, high organic C contents (mean 3.0 % $kg \cdot kg^{-1}$) and high dry bulk density (mean 1.5 $g \cdot cm^{-3}$). This set of conditions would cause the PTF to generate relatively large σ'_c estimates. These soil components are all characterized as Farmington soils and are largely responsible for the high mean σ'_c of 11.2 kPa.

Surface soil components in agricultural areas of Ontario have a significantly higher mean σ'_c value than in any of the Atlantic provinces (Table 3). These higher values are likely due to the significantly higher mean estimated clay contents in Ontario (24% $kg \cdot kg^{-1}$) compared with New Brunswick (16% $kg \cdot kg^{-1}$), Nova Scotia (15% $kg \cdot kg^{-1}$) and Prince Edward Island (10% $kg \cdot kg^{-1}$)(Table 5). Mean σ'_c values for the agricultural and non-agricultural subsurface soil components in Ontario were not found to be significantly different from those of the other provinces (Table 4). Mean σ'_c values for non-agricultural surface soil components in Ontario, however, were found to be significantly higher than those in New Brunswick and Nova Scotia and significantly lower than those in Newfoundland (Table 3). The latter finding will be discussed in Section 3.1.3.

3.1.3 Newfoundland

The SLC database contained no polygons in Newfoundland that were classified as agricultural land use areas. Of the non-agricultural areas, the mean σ'_c value for subsurface soil components (mean 5.3 kPa) was the lowest of all provinces, but was only significantly lower than New Brunswick and Nova Scotia. In the non-agricultural areas, only 11 surface soil components met the inclusion criteria. A closer look at the data revealed that each of these 11 soils had the same characteristics and produced a significantly higher mean value (mean 526 kPa) than the subsurface horizons and surface horizons of the other provinces in non-agricultural areas. All of these soil components have identical characteristics for clay content, dry bulk density and organic C content values. Each is characterized as a gravelly fine sandy loam and is, therefore, only marginally plastic. The lacks of variance in the physical soil data and PTF estimates, as well as the marginal plasticity, suggest that these results should be interpreted with caution.

3.1.4 Nova Scotia

The surface soils in Nova Scotia have a significantly lower mean σ'_c value than the subsurface soils in both agricultural and non-agricultural areas. In addition, the agricultural soil component means are significantly higher than the non-agricultural means for both their surface and the subsurface counterparts. These results are largely expected, although the very low mean σ'_c values for the surface soil components make it difficult to gauge the relative effects of tillage vs. natural pedoturbational processes on soil loosening. The mean σ'_c value for the agricultural surface soils is not significantly different from those of the other Maritime provinces, but is significantly lower than the Ontario mean value. The same pattern holds for the non-agricultural surface data, with the exception of the Newfoundland results. The reasons for this discrepancy were discussed in Section 3.1.3.

The mean σ'_c value for non-agricultural subsurface soil components is only significantly higher than the Newfoundland value. Map 2 shows the spatial distribution of the dominant subsurface soil components for agricultural areas in Nova Scotia. Large portions of the province were not assigned σ'_c estimates on the map, as the polygons were identified as dominantly non-agricultural.

3.1.5 Prince Edward Island

The Prince Edward Island data reflect trends that are similar to Nova Scotia for the agricultural areas. The mean σ'_c value for the agricultural surface soils (mean 0.6 kPa) was significantly lower than that of the agricultural subsurface soils (mean 20.7 kPa). However, the mean σ'_c value for the non-agricultural subsurface soils (126.7 kPa) was significantly higher than that of the agricultural subsurface soils (Table 4). The explanation for this latter spurious result is that only four non-agricultural subsurface components met the inclusion criteria. Due to the paucity of sample points, this result should be interpreted with caution. No data met the inclusion criteria for non-agricultural surface soil components.

The mean σ'_c value for the agricultural surface soils was lowest among all five provinces, although only significantly lower than the Ontario mean value (Table 3). Similarly, the mean σ'_c value for the agricultural subsurface soils was lowest among all five provinces, however none of these values were significantly different from one another (Table 4). The relatively low mean σ'_c value is a function of the low estimated plasticity (mean clay content 11%kg·kg^{-1}). Map 3 shows the spatial distribution of the σ'_c estimates for the dominant subsurface soil components in the agricultural areas of Prince Edward Island. Two polygons were not assigned a σ'_c estimate on the map because their dominant soil components were classed as non-agricultural.

3.1.6 New Brunswick

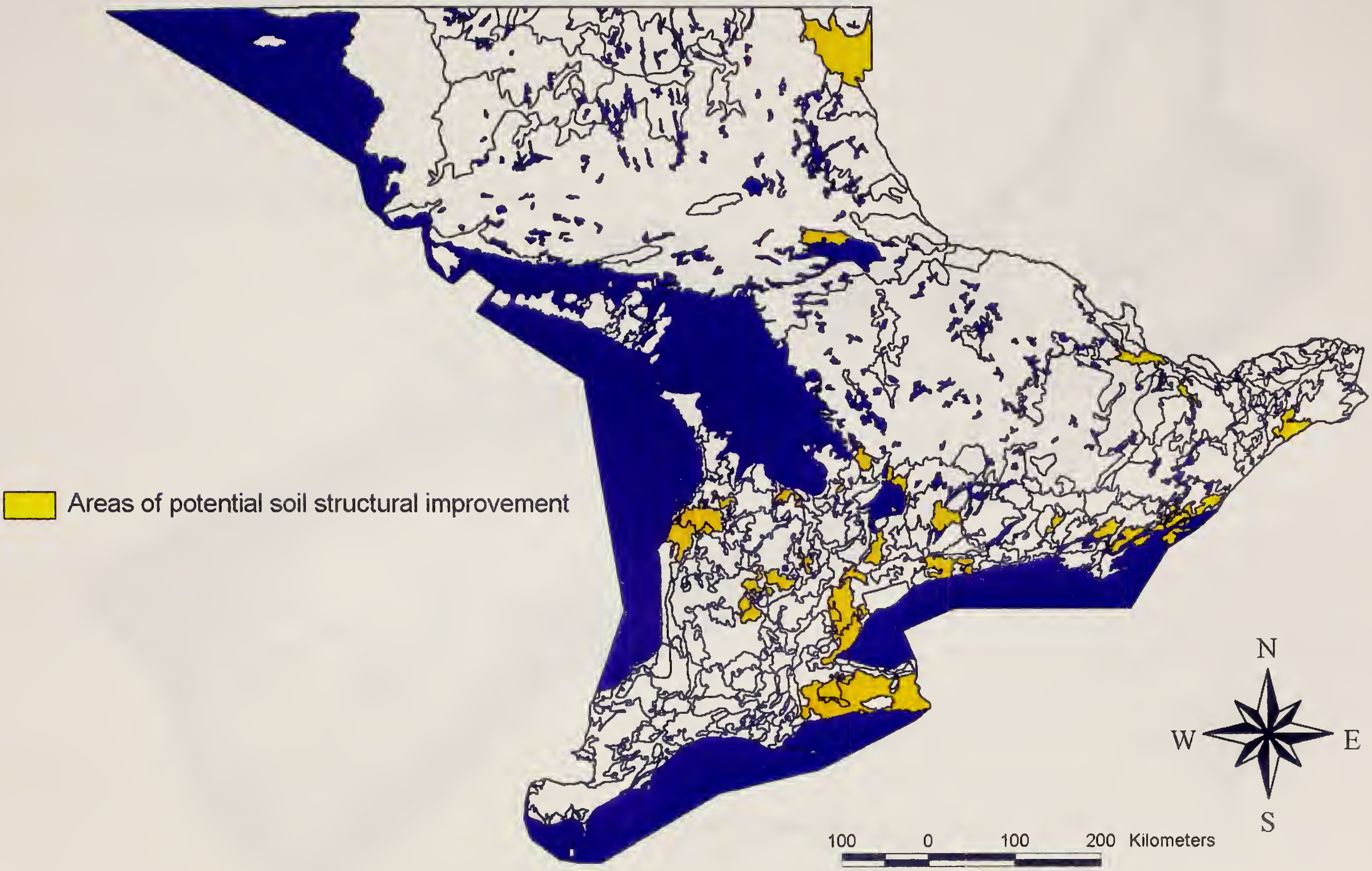
The mean σ'_c value for the agricultural surface components (mean 1.1 kPa) in New Brunswick is significantly lower than that of the subsurface components (mean 35.7 kPa). Likewise, the mean σ'_c value for non-agricultural subsurface components (mean 8.5 kPa) is significantly lower than that of the agricultural subsurface components. As noted in the Ontario data, the mean σ'_c value for agricultural surface components is lower than that of the non-agricultural surface components (mean 1.3 kPa), but in this case the difference is not significant. The degree of overconsolidation of agricultural surface components is significantly lower in New Brunswick than in Ontario, but is not significantly different from the other Maritime provinces. As noted earlier, however, the degree of overconsolidation in the subsurface soils does not differ statistically between provinces, but New Brunswick shows the highest degree at 35.7 kPa (Table 4). The relatively high organic C content (0.7 %kg·kg) probably contributes to this observation since increased organic C content, like clay content, has the effect of increasing soil plasticity. Map 4 shows the distribution of the σ'_c estimates for dominant subsurface soil components for the agricultural areas. Like Nova Scotia, large portions of the province were identified as dominantly non-agricultural and have not been assigned σ'_c estimates on the map.

In the non-agricultural areas, the mean σ'_c value of the subsurface components in New Brunswick is comparable to those of the other provinces, with the exception of Prince Edward Island. However, the mean σ'_c value is only significantly different from that of Newfoundland.

3.2 Areas of Potential Soil Structural Improvement

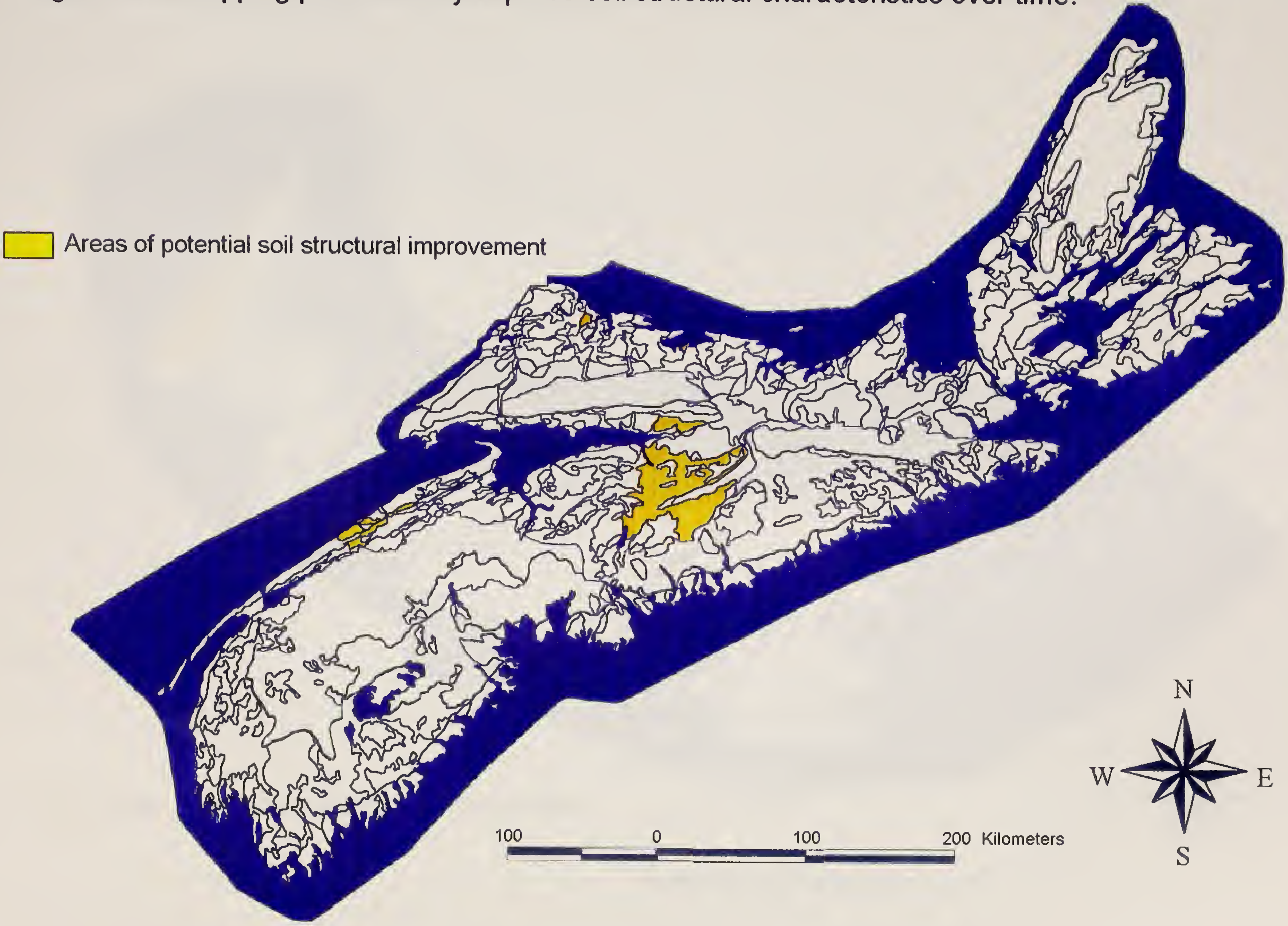
A frequency distribution was developed from the 1991 Census of Agriculture data for all five provinces that showed the fraction of total cropland within each polygon under land uses considered likely to lead to improved soil structure over time. It showed that polygons with $^1/_3$ or more of their land area under these cropping systems comprised approximately 50 % of all polygons in the eastern Canada study area. These polygons were cross-referenced with those where the σ'_c estimate was high (i.e., greater than 100 kPa) and the subsurface soil was, therefore, significantly overconsolidated and more likely to benefit from soil structure replenishing cropping systems (Kay, 1990). Maps 5 to 8 show the results of the cross-referencing for Ontario, Nova Scotia, Prince Edward Island and New Brunswick, respectively.

Map 5 shows a distribution of polygons across Ontario where the structural condition of overconsolidated subsurface soils may improve over time. In southwestern Ontario, large contiguous areas are identified in the Waterloo/Wellington region, the Halton/Peel region, southern Bruce County, and the "Haldimand clay plain" in the Regional Municipalities of Haldimand-Norfolk and Niagara. Smaller areas are scattered across central and eastern Ontario. In addition, the northeastern clay belt region (New Liskeard) and a region north of Lake Nipissing are identified. Maps 6 to 8 show that most of the areas identified as overconsolidated ($\sigma'_c > 100$kPa) in the Maritime provinces (Maps 2 to 4) may experience soil structural improvement over time (e.g., the Tantramarsh area of southeastern New Brunswick).

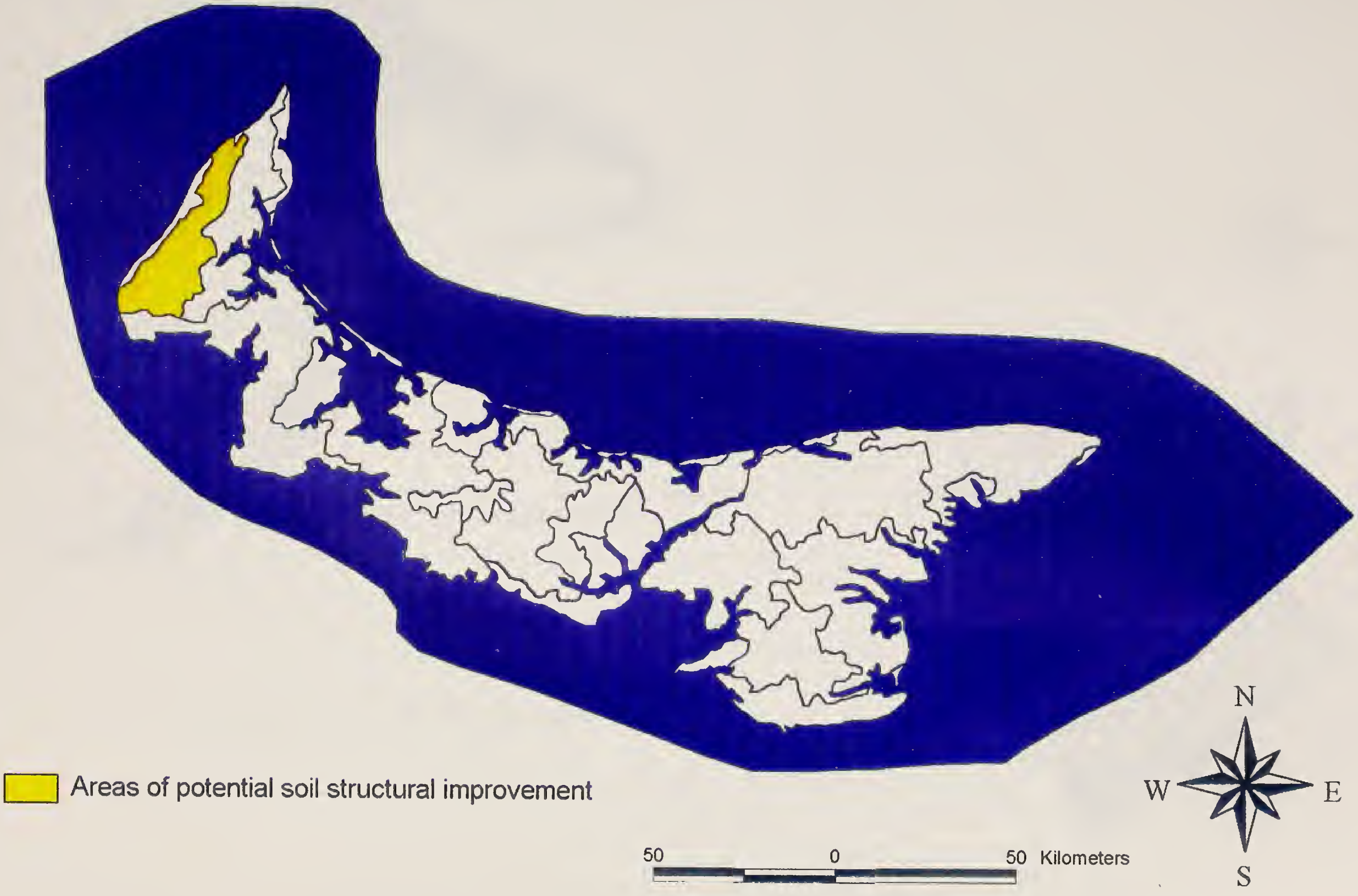


Map 5. Areas in the southern half of Ontario where the soils are significantly overconsolidated but the current agricultural cropping patterns may improve soil structural characteristics over time.

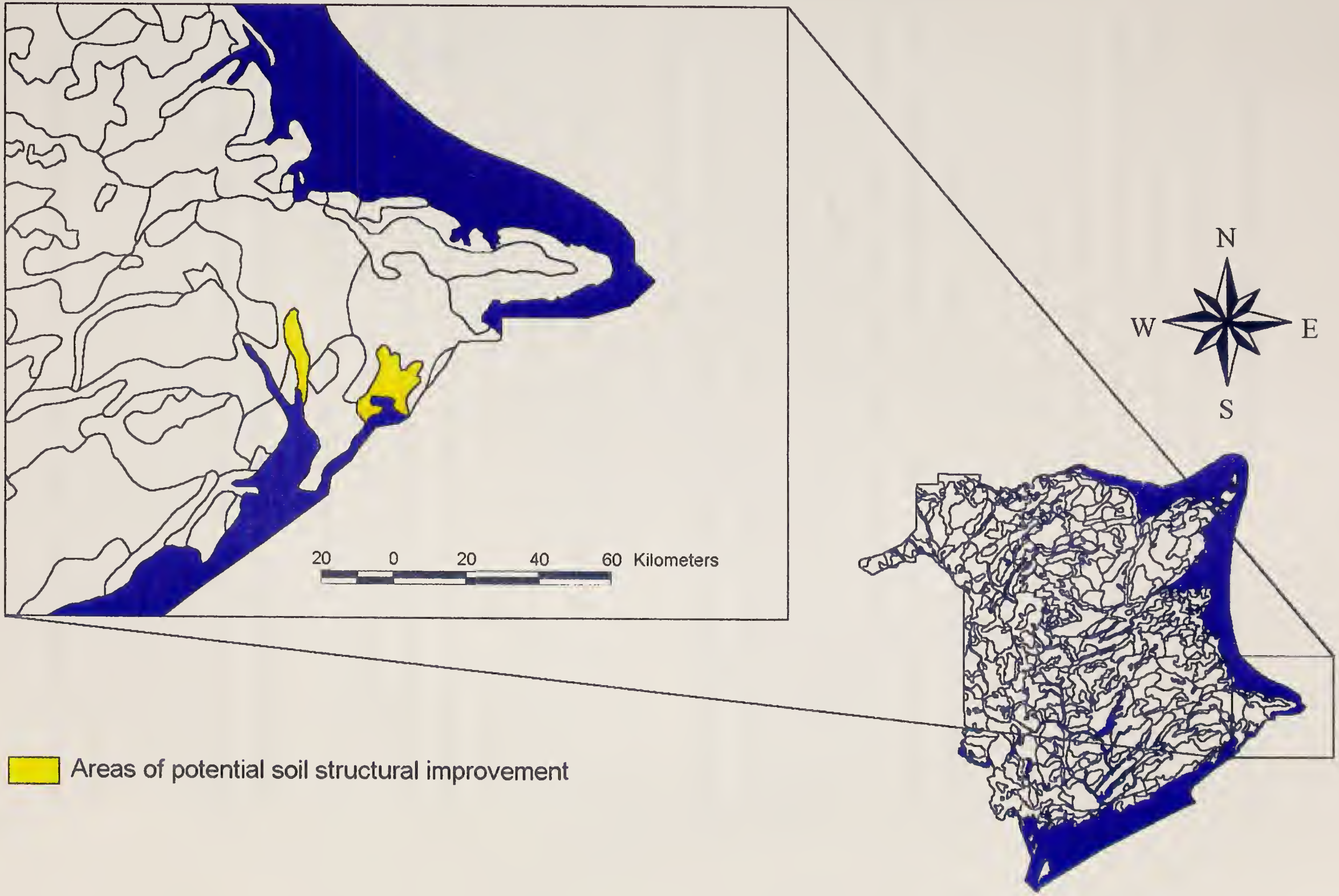
Map 6. Areas in Nova Scotia where the soils are significantly overconsolidated but the current agricultural cropping patterns may improve soil structural characteristics over time.



Map 7. Areas in Prince Edward Island where the soils are significantly overconsolidated but the current agricultural cropping patterns may improve soil structural characteristics over time.



Map 8. Areas in New Brunswick where the soils are significantly overconsolidated but the current agricultural cropping patterns may improve soil structural characteristics over time.



3.3 Areas of Potential Soil Structural Degradation

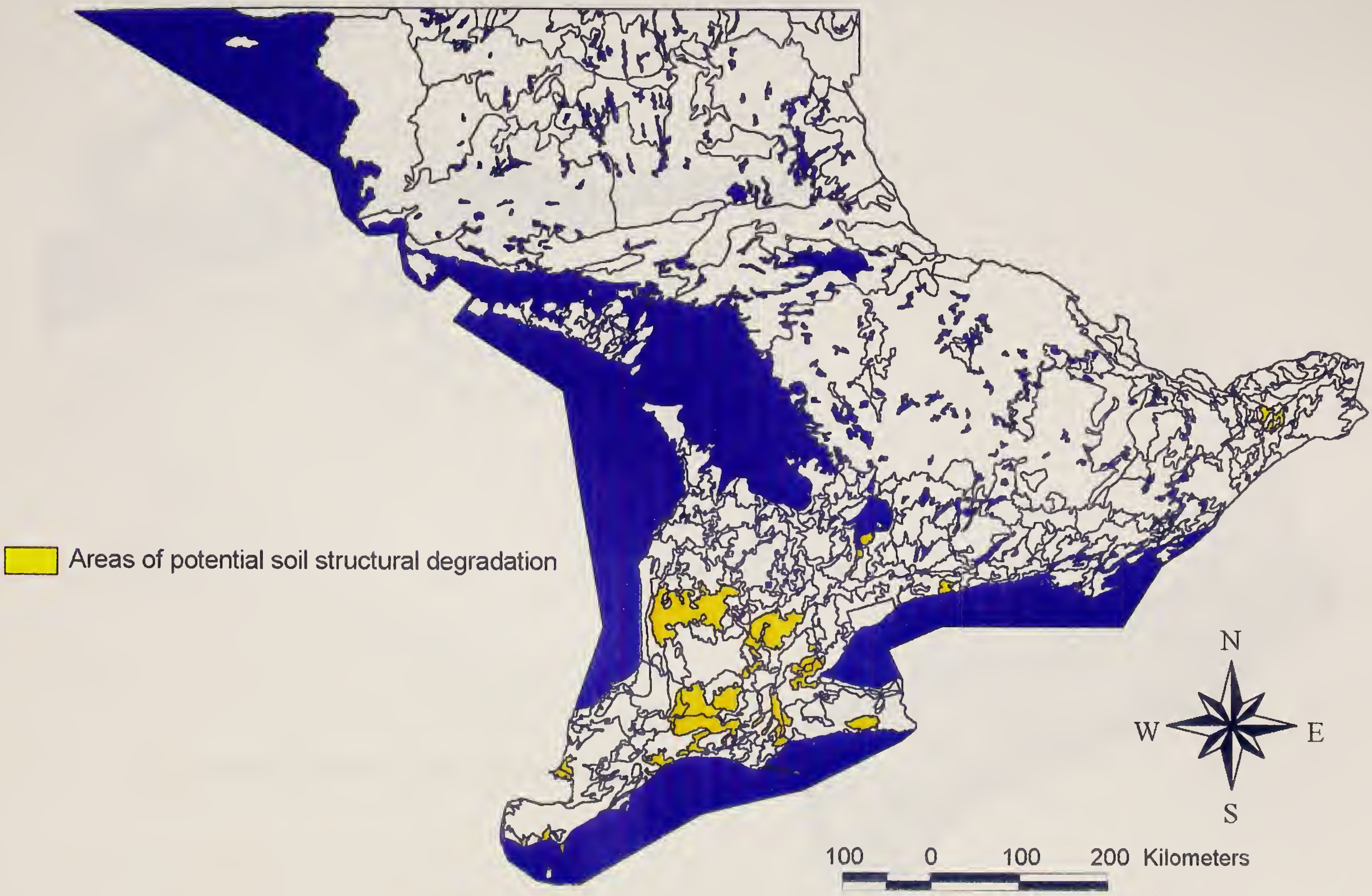
A frequency distribution was also generated for all five provinces that showed the fraction of total cropland within each polygon under land uses considered likely to cause further soil compaction or structural degradation over time. It showed that polygons with $^1/_5$ or more of their land area under these cropping systems comprised approximately 10% of all polygons in the eastern Canada study area. These polygons were cross-referenced with those where the σ'_c estimates were low (i.e., less than 100 kPa) and the subsurface soil was, therefore, not significantly overconsolidated and relatively susceptible to soil compaction from vehicular traffic and tillage operations. Maps 9 to 12 show the results of the cross-referencing for Ontario, Nova Scotia, Prince Edward Island and New Brunswick, respectively. The majority of the high risk areas in the eastern Canada study area are located in Ontario, centred on the Huron/Perth, Middlesex/Oxford and Waterloo/Wellington regions. New Brunswick and Prince Edward Island each have only a single polygon identified as high risk (upper Saint John River valley and central P.E.I., respectively), while Nova Scotia has two adjacent polygons at the east end of the Annapolis Valley.

3.4 Comparison of SLC Analysis and Detailed Soil Survey Analysis

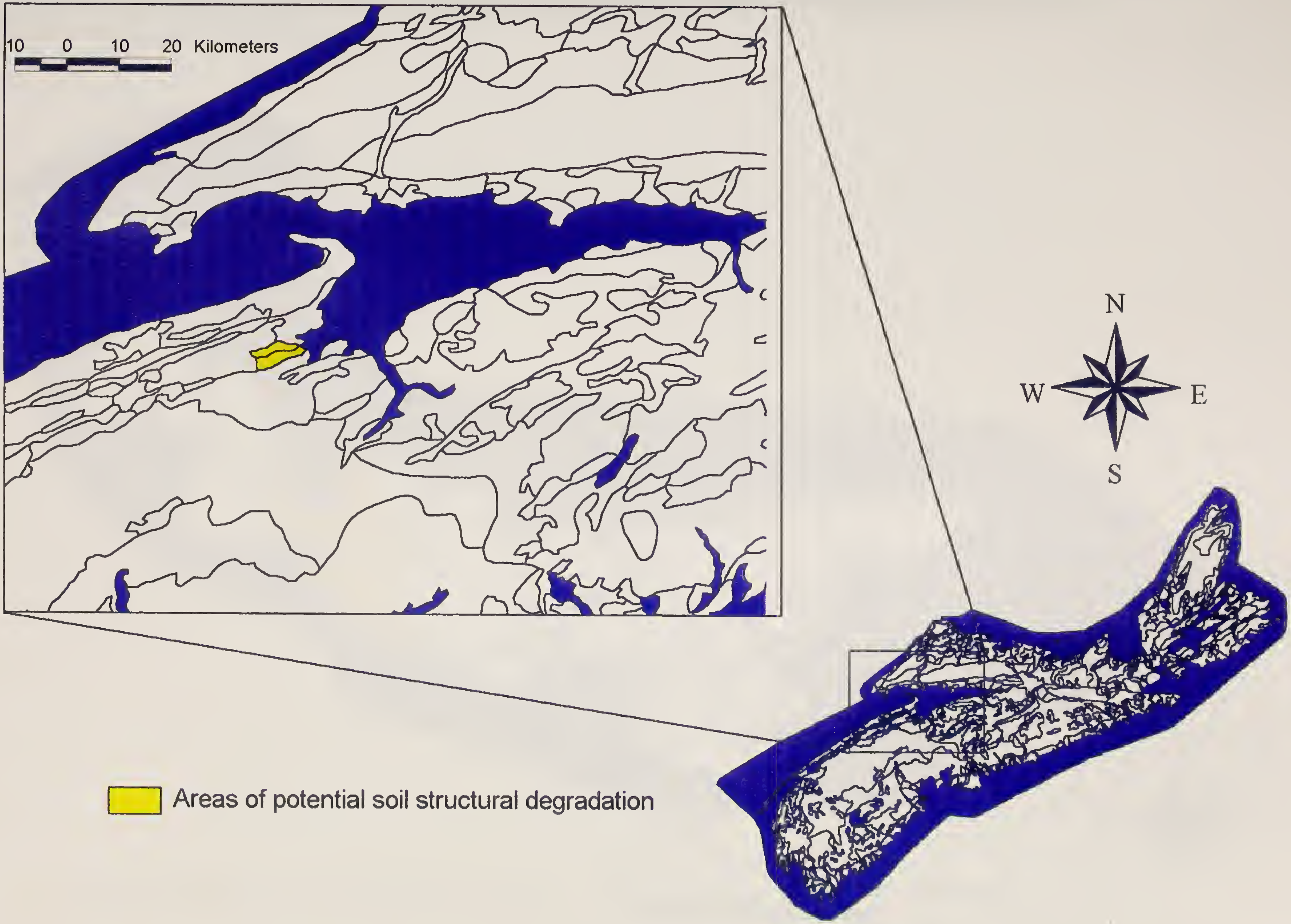
Table 6 summarizes the findings of the analysis presented for five counties in southwestern Ontario as reported in McBride and Joosse (1996). Table 7 summarizes the findings for the same five counties using the SLC dataset. These results show that the mean σ'_c estimated using the SLC dataset produces comparable results to those obtained using a more detailed dataset for the same area. The mean estimated σ'_c values for the surface and subsurface horizons were quite similar between the two databases.

While it was not possible to make a direct comparison of the means reported for the soil particle-size classes, an approximate comparison is possible by ordering the textural classes according to increasing clay contents. As seen in Table 6 (McBride and Joosse, 1996), the breakdown of the subsurface data by estimated clay content in Table 7 indicates that σ'_c estimates increase as clay contents rise. Again, the results are comparable with those of the SLC database, although the range of σ'_c values is broader for the SLC database. Therefore, it

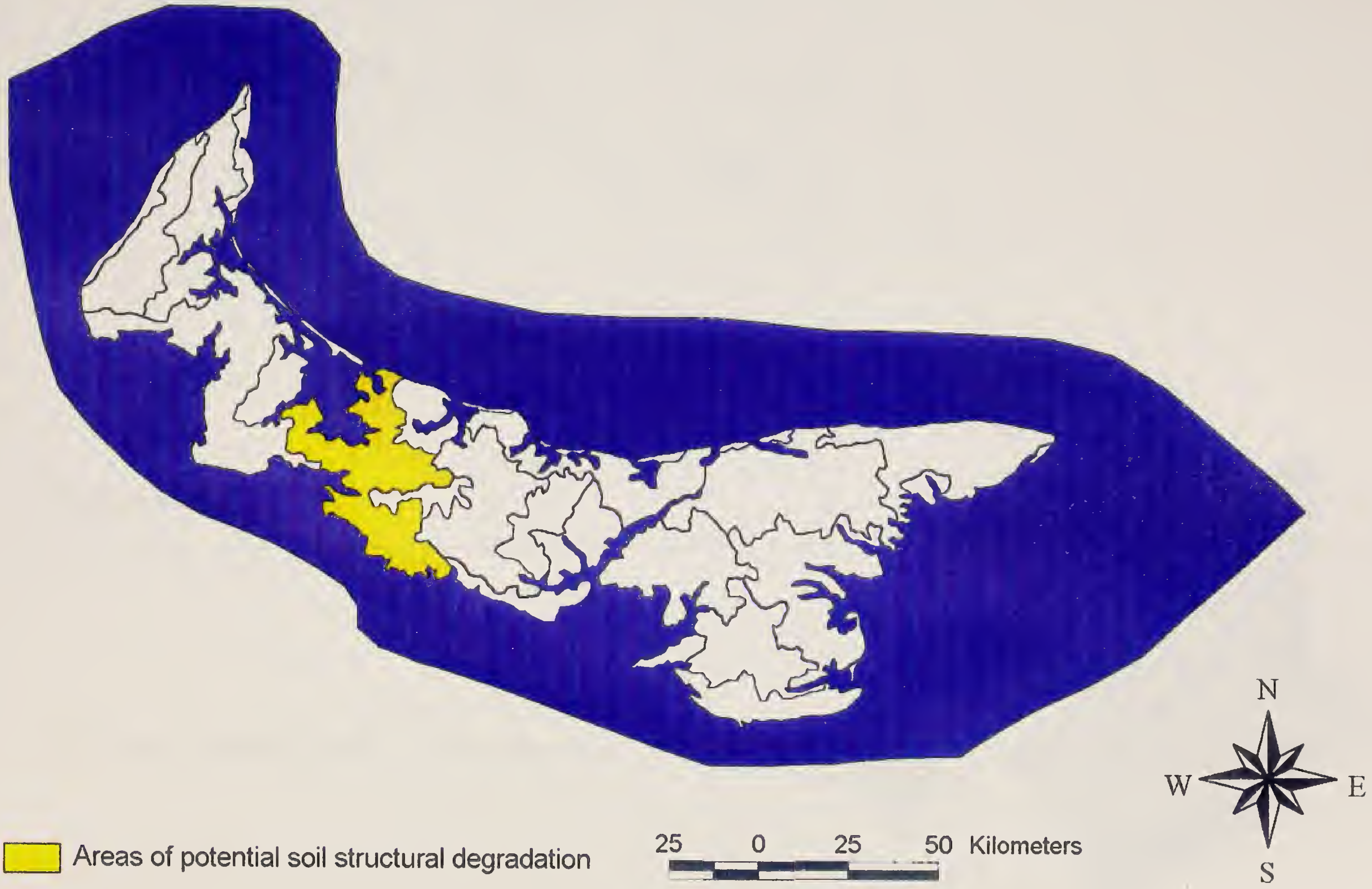
Map 9. Areas in the southern half of Ontario where the combination of significant soil susceptibility to compaction and agricultural cropping patterns are likely to degrade soil structural characteristics over time.



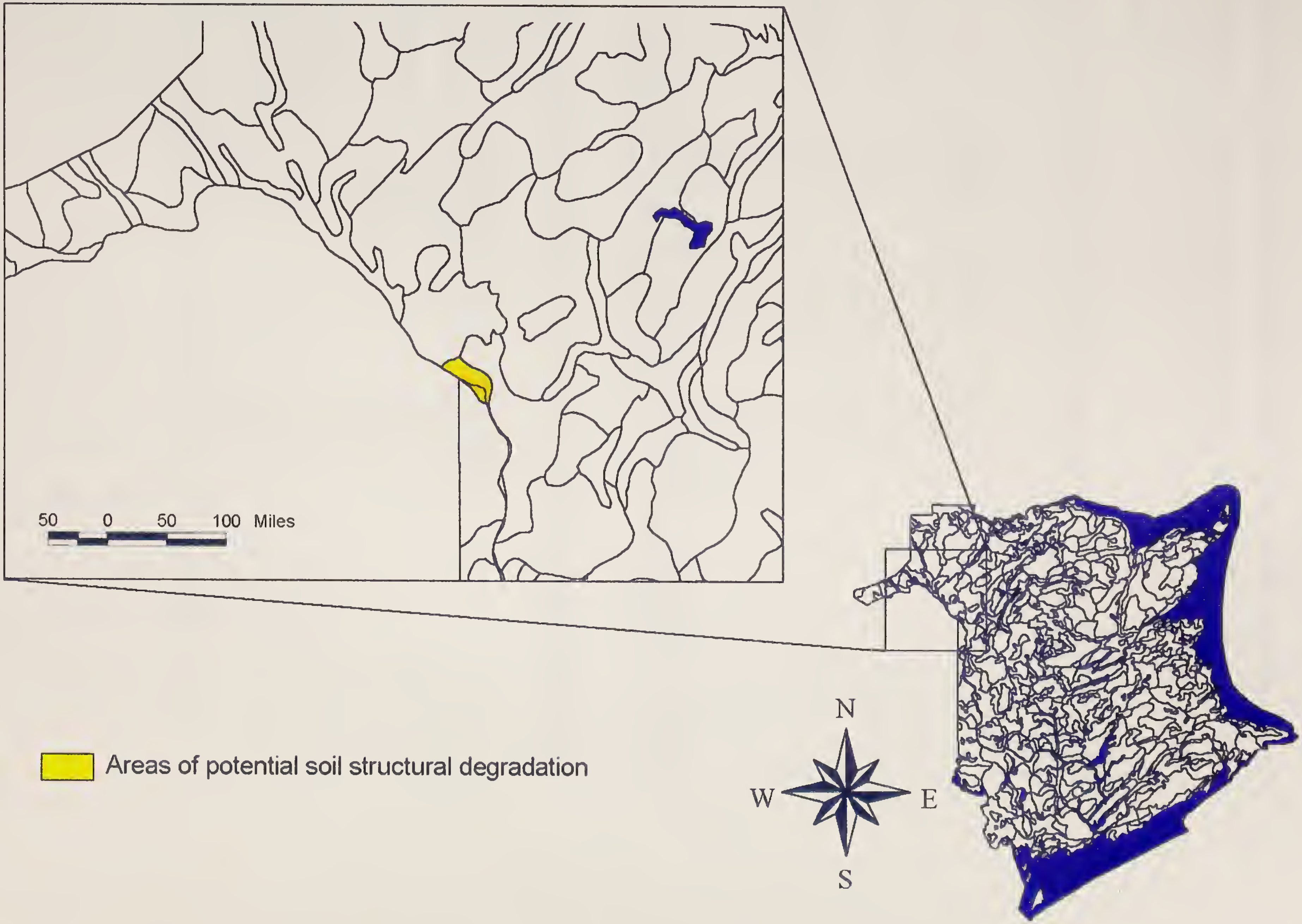
Map 10. Areas in Nova Scotia where the combination of significant soil susceptibility to compaction and agricultural cropping patterns are likely to degrade soil structural characteristics over time.



Map 11. Areas in Prince Edward Island where the combination of significant soil susceptibility to compaction and agricultural cropping patterns are likely to degrade soil structural characteristics over time.



Map 12. Areas in New Brunswick where the combination of significant soil susceptibility to compaction and agricultural cropping patterns are likely to degrade soil structural characteristics over time.



appears that the SLC data are reasonably reliable and are capable of providing realistic estimates of σ'_c using the PTF of McBride and Joosse (1996). The degree of data generalization inherent in the SLC data does not appear to inhibit their use in this type of application.

Table 6. Results of a General Linear Model analysis on σ'_c estimates of 127 subsoil horizons from a five-county region in southwestern Ontario (after McBride and Joosse, 1996).

Factor	Variable of classification [†]	Sample size (n)	Mean minimum possible σ'_c [‡]
			kPa
Soil Horizon	A	47	20 NA
	B	74	97 b
	C	53	138 a
Soil particle -size class	CL	15	16 c
	CS	4	13 c
	FL	23	81 b
	FS	12	107 b
	FC	59	151 a
	VFC	14	154 a

[†] CL = coarse loamy; CS = coarse silty; FL = fine loamy; FS = fine silty; FC = fine clayey; VFC = very fine clayey

[‡] Treatment means by factor followed by different lower case letters are significantly different at $P < 0.05$ ("NA" indicates that this group was not included in the analysis).

Table 7. Comparative results of σ'_c estimated for the same five-county region using the SLC database.

Factor	Variable of classification	Sample size (n)	Mean minimum possible σ'_c [‡]
			kPa
Soil Horizon	Surface	49	9 b
	Subsurface	52	99 a
Estimated clay content in subsurface soil (%kg·kg^{-1})	10	1	5 c
	14	3	7 bc
	17	7	1 c
	34	22	88 ab
	50	12	148 a
	70	7	271 a

[‡] Treatment means by factor followed by different lower case letters are significantly different at $P < 0.05$.

4. Summary and Conclusions

In summary, the three study objectives were fully achieved and the major findings have been summarized in both tabular and map form. For Objectives 1 and 2, maps were produced that show both the i) current state of the agricultural soil resource in the eastern Canada study area (i.e., degree of agricultural soil overconsolidation), and ii) maximum allowable ground pressure from agricultural vehicles before significant soil structural deterioration is likely to occur (Maps 1 - 4). Both of these interpretations are expressed in terms of preconsolidation stress (σ'_c) estimates (in kPa). Furthermore, a series of maps portray regions in eastern Canada where the risk of soil structural degradation is high (Maps 9 - 12) based on soil physical/mechanical properties and current agricultural cropping patterns (Objective 3). These analyses were most meaningful and revealing in southern Ontario and Prince Edward Island, where the vast majority of soil components were agricultural. This was not the case in Nova Scotia, New Brunswick and Newfoundland.

Two areas were also investigated that were not set out in the original study objectives. First, in juxtaposition to Objective 3, maps were created that depicted areas where cropping patterns may actually lead to an improvement in the structural condition of overconsolidated soils over time (Maps 5 - 8). This was done to produce a more balanced view of trends in soil quality in eastern Canada. For example, southern Ontario showed roughly equal areas of potentially soil structure replenishing and depleting lands. Furthermore, most map polygons identified as significantly overconsolidated (> 100 kPa) in the Maritime provinces also had more than $^1/_3$ of their area in soil structure replenishing crops. This was not the case, however, in Southern Ontario. Second, an attempt was made to assess the effect of data generalization at the 1:1M scale on the reliability of soil quality interpretations. Data assembled for this purpose from a five-county region in Ontario showed a high degree of interpretive consistency and reliability. There was also no evidence that the SLC data produced σ'_c estimates that were overly conservative, etc.

The more detailed findings of the study were found to be consistent with the expected trends in the data. In general, the degree of overconsolidation was lower in the surface soils than in the subsurface soils (i.e., lower σ'_c estimates), and higher in the agricultural areas than in the non-agricultural areas. Some exceptions were found, but this was often the result of small sample sizes or peculiarities in the SLC dataset.

Very little difference was found in the mean σ'_c estimates for subsurface layers among the provinces. There was greater variation in the σ'_c estimates for surface soils (with reasonably large sample sizes), but the mean σ'_c values were normally very low and hence the variation was of little importance. It is worth noting, however, that the agricultural surface soil components in Ontario had a significantly higher mean σ'_c value than those of the Maritime provinces. This may be a function of differences in inherent soil properties and/or in soil and crop management practices. The σ'_c estimates for the agricultural subsurface soils were higher than for the surface soils in all provinces, but the mean values were still relatively low (< 36 kPa) and not indicative of a serious or widespread soil overconsolidation problem in the eastern Canada study area.

This study showed that the most extensive areas believed to be at risk of further soil compaction within the eastern Canada study area were in southern Ontario. The limitations of the SLC database and procedures used, however, should be fully recognized by users of this information. The method used to identify areas at high risk was a very simple and arbitrary comparative assessment with a high risk area needing only a 20% occurrence of soil structure depleting land uses to qualify. These land use data were compared only to the consolidation state of the dominant soil component within a given polygon, and it was not possible in the SLC database to ascertain whether there was any correspondence in the locations of the dominant soil component and the land use of concern. The same precaution applies to the information on areas likely to undergo soil structural improvement over time.

Overall, the SLC database provided reliable information for a provincial-level analysis of an agri-environmental indicator (i.e., trends and spatial distribution of the degree of soil overconsolidation) for an extensive eastern Canada study area.

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