Use of Digital Image Analysis and GIS to Assess Regional Soil Compaction Risk

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Abstract

A soil compaction risk study was undertaken in an agricultural region of southern Ontario, Canada. The objective was to identify land areas that are highly susceptible to traffic- and tillage-induced soil compaction given their soil mechanical properties and their use for intensive row crop production (including continuous corn monoculturing) under local climatic conditions. Spatial information on the distribution of various agricultural crops in relation to the major soil associations was acquired using an integrated approach involving digital image analysis and GIS. Error matrices showed that the user's accuracy of the crop cover classification at the field level was better than 80 percent for all major crop types, and the correspondence to census information was equally good. The soil associations most vulnerable to compaction in three local municipalities where row crops dominate included about 75 km² of medium-textured soils (about 6 percent of the total cropped area). The silty clay loam tills were identified as being particularly at risk due to observed cropping practices.

Introduction

Increasing concern in North America about the long-term sustainability of soil resources used to meet food and environmental needs has resulted in numerous soil quality monitoring and assessment programs aimed at quantifying soil quality indicators and examining the impact of various forms of soil degradation (e.g., water and wind erosion, compaction, acidification) on key chemical, physical, and biological characteristics (Doran and Parkin, 1994). Compacted or overconsolidated subsoils can result from natural causes (e.g., basal till parent material, effective stresses from desiccation) or from human activity (e.g., mechanical stresses from wheel traffic or tillage operations). Wheel traffic from heavy vehicles, for example, can compress soils to varying degrees throughout the plant root zone, often causing increased mechanical strength and decreased air and water permeability. This condition can impede root elongation and significantly reduce crop growth and yield (Soane and van Ouwerkerk, 1994).

Very little is known about the current state of natural soil consolidation or anthropogenic soil compaction in the region of the Canadian Great Lakes basin where intensive agriculture is the dominant land use. Cursory investigations using soil morphological characteristics as physical indicators of soil quality have indicated that 50 percent or more of the fine-textured soils in southwestern Ontario are moderately to severely compacted, and that soil compaction in general may be costing the Ontario agricultural economy over $20M annually (Science Council of Canada, 1986; Can-Ag Enterprises, 1988). Furthermore, compaction is the form of soil degradation that the corn (maize) growers across southern Ontario have identified as being the most widespread and serious soil conservation problem on their farms (Deloitte and Touche, 1991).

In response to this deficiency in basic knowledge of the soil structural condition and degree of soil overconsolidation in this region, the Soil Quality Evaluation Program (S.Q.E.P.) was initiated by Agriculture and Agri-Food Canada in 1991 under the comprehensive National Soil Conservation Program (Acton, 1994). Included in the broad objectives of the "soil structure" component of the S.Q.E.P. were (1) characterizing the present structural integrity of agricultural soils located on several dominant landscapes in a selected region, (2) ascertaining the risk of further damage from row crop monoculture cropping systems, and (3) locating the land areas at highest risk. The Regional Municipality of Haldimand-Norfolk in southern Ontario (Figure 1) was selected for this risk assessment due to (1) the wide textural range of the soils, (2) the availability of reconnaissance soil survey mapping (scale 1:100,000) derived from a recent and more detailed soil inventory upgrade (scale 1:25,000), and (3) the availability of ancillary hydrological and soil characterization data.

Representative soil profiles were first sampled from the major soil associations in the regional municipality, and the compressibility characteristics and susceptibility to compaction were measured in the laboratory (Veenhof and McBride, 1996). The clay-rich soils of the region were generally found to be quite overconsolidated, most likely a result of natural processes including soil desiccation. A soil water balance model was then applied to the soil and climatic conditions in this part of the province in order to determine the probability of significant soil compaction occurring in the field at those times during the season when wheel traffic and tillage are most likely to occur under a continuous corn cropping system (McBride, 1994). Of the soil groups that were less severely overconsolidated, the medium-textured soils were found to be most susceptible to total soil porosity loss when field operations are undertaken under less than optimum soil strength conditions (e.g., late fall harvesting of corn). As a result, the silty clay loam tills and lacustrine silt loams and silty clays were singled out for the final stage of the risk assessment for corn production systems.

This paper reports on the final stage of the soil compac-

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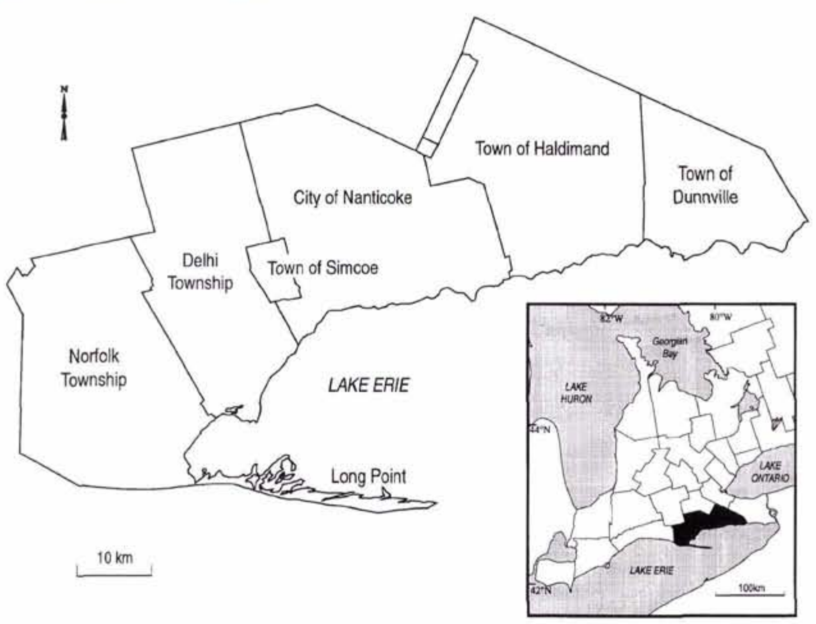

Figure 1. Location of the Regional Municipality of Haldimand-Norfolk, Ontario, and the local municipalities within its boundaries.

ion risk analysis, which required current information on the distribution of agricultural crops (primarily corn and other row crops) in relation to the major soil associations mapped in the regional municipality. Existing agricultural land-use mapping for this region was outdated and was based on farm system categories rather than field-level identification of crop types. The approach adopted for this stage of the analysis was to use a GIS to combine and integrate classified Landsat 5 Thematic Mapper (TM) images with digital soils data which clearly delineated those soil associations most susceptible to compaction (Steffensen and Mack, 1986).

Palylyk *et al.* (1991) utilized two successive years of crop cover information derived from Landsat TM imagery along with county level soil survey mapping to predict soil erosion risk at regional scales in Alberta. Other investigations have successfully integrated Landsat TM data with soil information to evaluate agricultural nonpoint-source pollution within watersheds (Sivertun *et al.*, 1988; Jakubauskas *et al.*, 1992) or to develop a multi-purpose land information system for rural resource planning (Ventura *et al.*, 1988).

Zhou *et al.* (1991) have pointed out some of the pitfalls in extrapolating field level observations or point measures of soil properties to regional or provincial scale soil mapping units. Therefore, no attempt was made in this study to map the spatial distribution of classes of soil compaction susceptibility for the entire region. The emphasis instead was on identification of map units comprised of medium-textured soil associations where corn was grown for at least two consecutive years.

The main objective of this phase of the S.Q.E.P. study was to investigate the co-occurrence within the Regional Municipality of Haldimand-Norfolk of (1) medium-textured soil associations (scale 1:100,000) that are highly susceptible to tillage- and traffic-induced soil compaction during the corn planting and harvesting periods, and (2) fields where continuous corn is the dominant cropping system. With two consecutive years of crop cover information (1990, 1991), an attempt would also be made to identify areas where the present agricultural use may include row crop monoculturing (e.g., corn and soybeans) or corn in rotation with other common field crops. Field data and data assembled from the 1991 Census of Agriculture (Statistics Canada, 1992) were used to verify the thematic accuracy of the crop cover classification derived from image analysis at the field level and at the local municipality level, respectively.

Methods and Procedures

Preliminary Data Needs

The process of spatial data acquisition and manipulation involved the use of both digital image analysis and geographical information system (GIS) techniques for which the necessary data were assembled. Landsat 5 TM data were acquired for the 1 August 1990 and 3 July 1991 overpass dates. The road network and administrative boundaries (Figure 1) were also digitized using a planimetrically accurate base map (scale 1:100,000). Coordinate registration was by decimal degrees (latitude/longitude) using four well defined and spatially distributed ground control points taken from available Ontario Base Maps (scale 1:10,000), because there was no grid or geodetic referencing on the 1:100,000 scale base map of the region. These vector files were then converted to the UTM projection system (Zone 17). All layers of spatial data used in this study (i.e., classified images and soil coverage) were registered to these vector files.

Crop Cover Classification

Crop cover information was derived from Landsat TM imagery for two successive growing seasons (1990, 1991). Acceptable quarter-scene images (less than 5 percent cloud cover) for these years were obtained for dates during the growing season which would allow maximum crop type discrimination (Wanjura and Hatfield, 1988). These quarter scenes did not provide full coverage of the regional municipality, effectively eliminating the eastern extremity (i.e., the local municipality of Dunnville) from this analysis (Figure 1). Use of imagery for several dates within a single growing season is likely to improve the thematic accuracy of crop classification, because it can provide more spectral information at different and critical crop development stages (Lillesand and

Table 1. Error Matrix for the Supervised Classification of the 1990 TM Imagery.

	Corn	Soybeans	Tobacco	Hay & Pasture	Cereal Grains	Forest	Urban	Total	Errors of Commission (%)
Corn	48	0	0	0	0	0	0	48	0
Soybeans	6	2	0	0	1	0	0	9	78
Tobacco	0	0	4	0	0	0	0	4	0
Hay & Pasture	0	0	0	4	0	0	0	4	0
Cereal Grains	0	0	2	0	5	0	0	7	29
Forest	0	0	0	0	0	0	0	0	—
Urban	1	3	0	0	1	0	0	5	—
Total	55	5	6	4	7	0	0	77	
Errors of Omission (%)	13	60	33	0	29	—	—		

Kappa-coefficient = 0.66

Table 2. Band Correlation Matrix for the 1991 Digital Image Data.

TM Band #	1	2	3	4	5	7
1	1.00					
2	0.95	1.00				
3	0.85	0.96	1.00			
4	0.50	0.62	0.62	1.00		
5	0.59	0.75	0.83	0.88	1.00	
7	0.63	0.81	0.91	0.73	0.95	1.00

Kieffer, 1979; Thenkabail *et al.*, 1994). There was no opportunity, however, to use multiple dates in this study due to unacceptable levels of cloud cover on images from other overpass dates during the 1990/91 growing seasons.

The S.Q.E.P. project began in January 1991, so field level reference data on crop cover for the 1990 growing season were collected during the early spring of 1991. Corn was one of the few 1990 crop types that could be confidently identified in the field at this time of year based on the presence of corn crop residue. Some crops other than corn were positively identified in instances where the crop had not been harvested in 1990, or where sufficient crop residue remained on the surface and had not been incorporated by fall tillage. Five crop types were identified in the field and subsequently on the 1990 image (Table 1).

A more intensive field inventory of crop cover was carried out during the 1991 growing season to correspond to the 3 July 1991 overpass date. One large tract was delineated within each of the three major physiographic areas in the regional municipality (Plate 1): the Norfolk sand plain, the Haldimand clay plain, and the medium-textured lacustrine deposits situated between the two (Chapman and Putnam, 1984; Presant and Acton, 1984). The location and type of common field crops were observed and recorded for about 300 fields. This more comprehensive set of reference data improved the crop type discrimination on the 1991 image classification, particularly for tobacco and winter/spring cereal grains. The 1991 reference data were partitioned into training and validation data sets. The training data set (about 100 fields) was used in the supervised classification procedure, while the validation data set (about 200 fields) was used for thematic accuracy assessment.

A supervised classification of the two TM images was performed using a maximum-likelihood classifier. The Landsat TM bands used to establish spectral reflectance patterns of the surface vegetation were selected based on previous research and from an evaluation of the band correlation matrix. Kenk *et al.* (1988) have recommended that a minimum of four bands be used for ground cover classification using Landsat TM imagery. Others have argued that three TM bands are sufficient for crop cover classification, and that additional bands improve the thematic accuracy only marginally (Townshend, 1984; Chen *et al.*, 1986). For corn and soybeans, Thenkabail *et al.* (1994) found that vegetation indices that included mid-infrared bands (e.g., Landsat TM band 5) were most suited for detection of differences in crop growth parameters and canopy structure.

Landsat TM bands 1, 2, 3, and 5 were used for the supervised classification of the 1990 imagery as they showed the least amount of correlation within the band correlation matrix. The number of bands selected from the 1991 TM imagery was reduced to three (bands 3, 4, and 5) because of the more substantial field data and the relatively low coefficients in the band correlation matrix (Table 2).

The 1990 and 1991 classified images were registered to the road network vector files for the regional municipality using 15 to 20 evenly distributed ground control points. Polynomial transformations were used for image rectification, producing root-mean-square errors (RMSE) of 0.282 and 0.865 pixel units for the 1990 and 1991 images, respectively. A registration graphic display was used to select the most appropriate polynomial order in rectifying and registering the image file, thereby achieving optimum positional accuracy (Janssen and van der Wel, 1994).

Error matrices and Kappa-coefficients (κ) were generated for the 1990 and 1991 image classifications and are given in Tables 1 and 3, respectively (Story and Congalton, 1986; Janssen and van der Wel, 1994). The errors of omission and

Table 3. Error Matrix for the Supervised Classification of the 1991 TM Imagery.

	Corn	Soybeans	Cereal Grains	Hay & Pasture	Tobacco	Forest	Total	Errors of Commission (%)
Corn	44	1	1	1	3	0	50	12
Soybeans	1	36	2	2	3	0	44	18
Cereal Grains	0	1	51	0	0	0	52	2
Hay & Pasture	1	0	1	13	0	1	16	19
Tobacco	0	0	0	0	36	0	36	0
Forest	0	0	0	0	0	10	10	0
Total	46	38	55	16	42	11	208	
Errors of Omission (%)	4	5	7	19	14	9		

Kappa-coefficient = 0.89

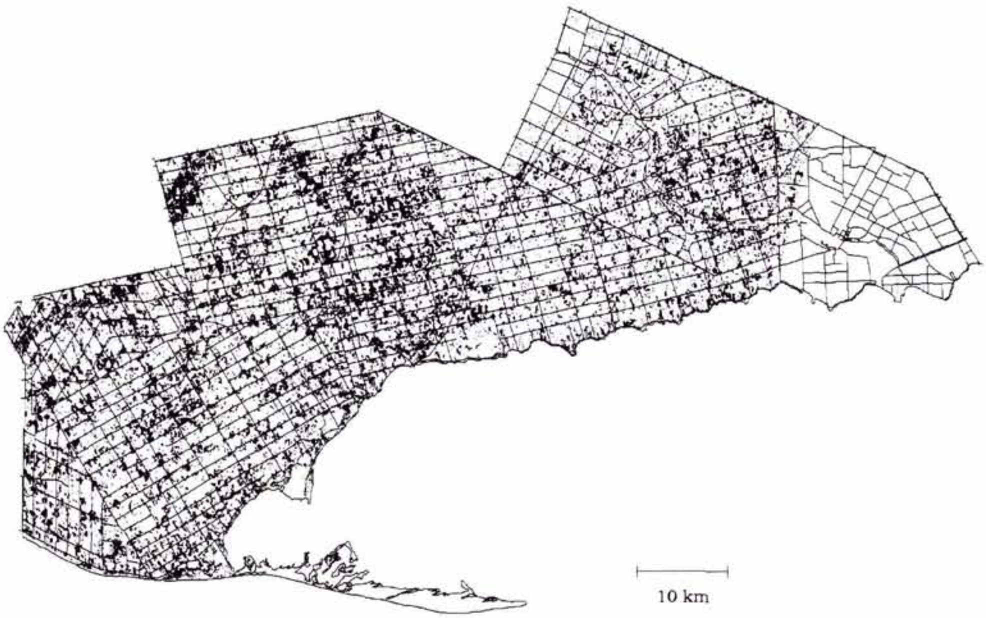

Figure 2. Corn cover map for the R.M. of Haldimand-Norfolk in 1991 as derived from digital image analysis of Landsat 5 TM imagery.

commission were based on whole field (not individual pixel) level assessments, and represented the first of two steps in evaluating the thematic accuracy of the classified images. It is the errors of commission that determine the reliability, or user's accuracy, of the classified image (Janssen and van der Wel, 1994). The κ-coefficient provides a Chi-square assessment of agreement between the reference data and the classified image as a whole and takes into account chance agreement in its derivation (Campbell, 1986; Janssen and van der Wel, 1994).

A modal filter was applied to the geocorrected digital raster files to fill in any unclassified areas within a field of known crop type. These files were exported to the GIS for subsequent overlay and cross-tabulation analyses with the soils mapping.

Reconnaissance Soil Association Mapping

The generalized soil association mapping (scale 1:100,000) that was published by Agriculture Canada (L.R.R.I., 1985) was chosen over the more detailed 1:25,000-scale inventory available for the region (Presant and Acton, 1984). The soil association level of mapping resolution was thought to be more appropriate to the overall study objectives and more consistent with the types of regional soil compactibility generalizations reported in McBride (1994). The 1:100,000-scale mapping, however, was not available in digital form from the Cartography Section of the L.R.R.I. at the time that this study was undertaken, so it was digitized with the registration error maintained at 0.001 or less across the coverage area (Plate 1). These vector files were then imported into the GIS and converted into a raster data model consistent with the classified imagery.

Results and Discussion

A number of maps, area reports, and cross-tabulations were generated with the GIS. The impact on the training stage of having a more comprehensive set of reference data for thematic accuracy assessment in 1991 is reflected in the higher κ-coefficient of 0.89 for the 1991 classified image (Table 3) compared to κ=0.66 for 1990 (Table 1). The user's accuracy for all five main crop types (i.e., corn, soybeans, cereal grains, hay/pasture, and tobacco) was over 80 percent in 1991 (Table 3). Figure 2 shows the corn producing areas in 1991 (user's accuracy of 88 percent).

Area reports were generated by local municipality based on cross-tabulation of the soil association map (Plate 1) with the 1990 corn cover map, the 1991 crop cover map (Figure 2 shows only the corn coverage), and the 1990/91 map of crop rotations involving corn (Plate 2). Only the corn cover mapping was used from the 1990 imagery (user's accuracy of 100 percent) due to the lesser confidence in the 1990 classification for the other crop types with limited reference data (Table 1). In general, all of the above reports showed relatively low contingency coefficients (0.204 to 0.499), Tschurprow's T statistics (0.058 to 0.180), and Cramer's V statistics (0.063 to 0.218), suggesting that the spatial correlation between crops grown during a particular year and the soil associations across the region as a whole was not high (Reynolds, 1977). When compared to regional averages, however, some soil associations did show proportionately higher or lower than average use for corn production within local municipalities (Tables 4 and 5) as will now be discussed.

Digital estimates of corn area for 1991 are summarized in Table 4 for three of the local municipalities where corn and other row crops dominate. These digital estimates were compared with area estimates from the 1991 Census of Agriculture (Statistics Canada, 1992) as an additional means of thematic accuracy assessment, independent of the error matrix given in Table 3. The corn area totals reported from the census (Table 4) include grain corn, silage corn, and sweet corn crop types and show a reasonably good correspondence with the Landsat derived estimates of total corn area. On average, between 21 percent and 23 percent of the area of these three local municipalities that was cleared and available for agriculture in 1991 was planted to corn in that year. Also shown in Table 4 is the distribution of corn area in relation to the major soil associations for these localities. In general, these percentages are consistent with the mean for the local municipality as a whole, although there was proportionately less corn grown on the silty clay and heavy clay soils of Nor-

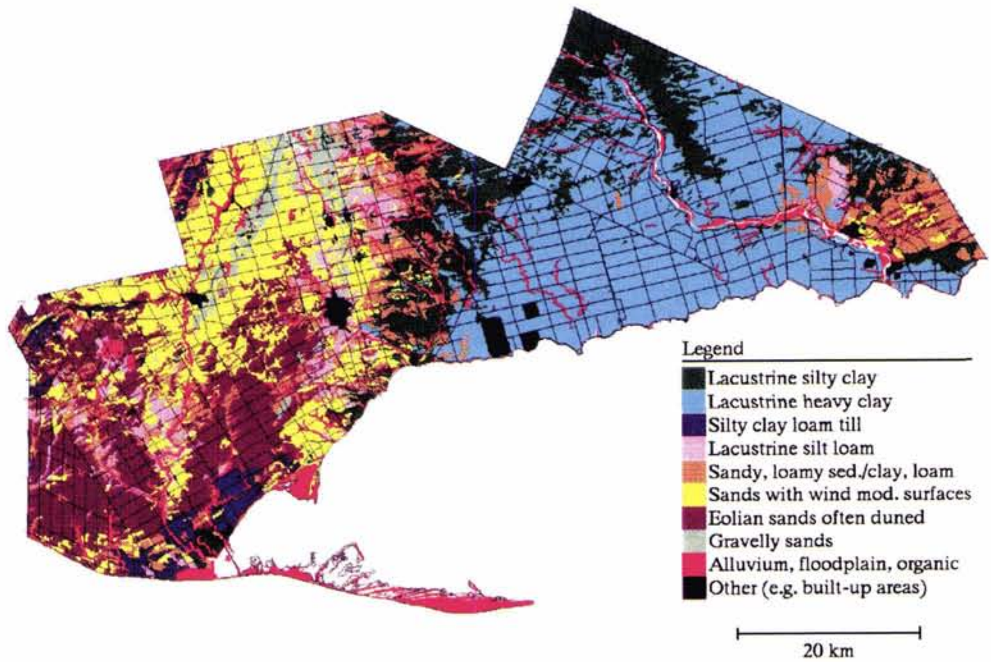

Plate 1. Generalized soil inventory map (original mapped scale of 1:100,000) for the R.M. of Haldimand-Norfolk (after L.R.R.I., 1985).

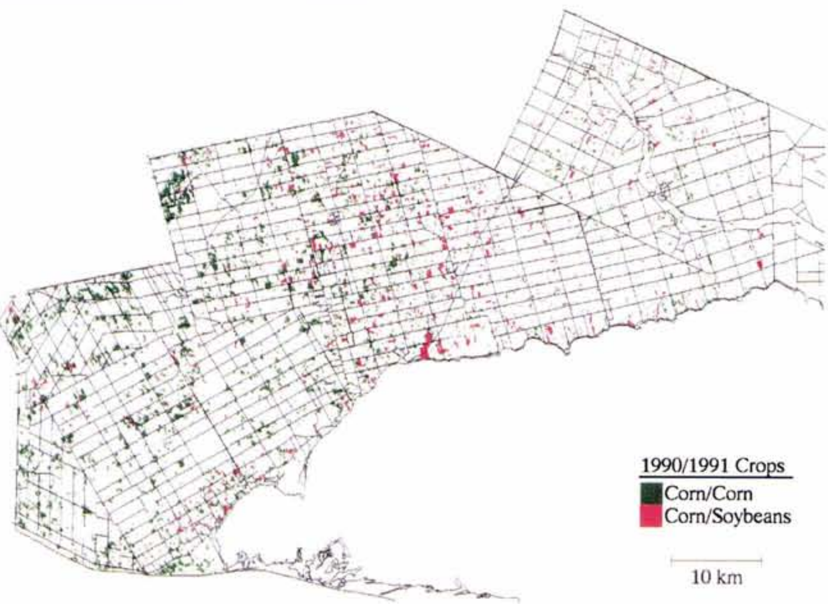

Plate 2. Crop cover map showing those areas within the R.M. of Haldimand-Norfolk where corn in 1990 was followed by corn or soybeans in 1991 (i.e., row crop monoculturing).

folk and Nanticoke, respectively, and proportionately more grown on the silty clay loam tills of Delhi.

Table 4 also provides information on the total area of land that is most susceptible to tillage- and traffic-induced soil compaction during corn planting and harvesting periods given (1) its present use for corn production, and (2) the soil compression behavior and soil compaction risk assessment results for these soil associations (McBride, 1994; Veenhof and McBride, 1996). These high risk soil associations included about 3300 ha of mainly lacustrine silty clays (Brantford, Beverly, and Toledo soil series), about 1700 ha of mainly silty clay loam tills (Muriel, Gobles, and Kelvin soil series), and about 2400 ha of mainly lacustrine silt loams (Brant, Tuscola, and Colwood soil series). This amounts to a total area of about 75 km^2, or approximately 6 percent of the total cropped area.

Table 5 shows a significant reduction in area totals where high compaction risk soils coincide with areas where

TABLE 4. CROSS-TABULATION RESULTS OF 1991 CROP COVER WITH THE GENERALIZED SOIL INVENTORY FOR THE R.M. OF HALDIMAND-NORFOLK.

Soil Associations (Scale 1:100,000)[†]		Corn Area in 1991 by Local Municipality (ha)		
Mode of Soil Deposition	Corresponding Soil Series Names (from 1:25,000 Scale Mapping)	Township of Norfolk	Township of Delhi	City of Nanticoke
*Mainly lacustrine silty clay	Brantford, Beverly, Toledo	121 (17%)[‡]	160 (29%)	3054 (25%)
Mainly lacustrine heavy clay	Smithville, Haldimand, Lincoln	—	—	2504 (15%)
*Mainly silty clay loam till	Muriel, Gobles, Kelvin	1194 (28%)	536 (48%)	—
*Mainly lacustrine silt loam	Brant, Tuscola, Colwood	870 (27%)	368 (26%)	1119 (37%)
40-100 cm of sandy or loamy sediments over lacustrine clays or loams	Brookton, Berrien, Wauseon, Walsher, Vittoria, Silver Hill, Tavistock, Maplewood	1238 (30%)	874 (31%)	1721 (28%)
Mainly lacustrine sands with wind-modified surfaces	Fox, Brady, Granby, Wattford, Normandale, St. Williams, Lowbanks	2175 (24%)	3367 (21%)	1233 (28%)
Mainly eolian sands at least 100 cm thick, often duned	Plainfield, Walsingham, Waterin	4121 (23%)	1944 (23%)	162 (26%)
Gravelly sands of fluvial or till derivation, or 40 to 100 cm of sandy sediments over gravelly sands	Burford, Wilsonville, Scotland, Oakland, Vanessa	41 (3%)	756 (22%)	541 (26%)
	Landsat TM Classified Image Area Total for Corn (Hectares):-	9760	8005	10334
	Corn Area as a Percent of the Local Municipality Area that Is Cleared and Available for Agriculture:-	23.0%	22.2%	20.8%
	1991 Census Area Total for Corn (Hectares):-	9634	6736	10195

[†]after L.R.R.I. (1985) and Presant and Acton (1984)
[‡]the number in brackets is the proportion (expressed as a %) of 1991 corn area to the total area cleared and available for agriculture (by soil association and local municipality)
*soil associations most susceptible to compaction (McBride, 1994; Veenhof and McBride, 1996)

TABLE 5. CROSS-TABULATION RESULTS OF AREAS PLANTED TO CORN FOR TWO CONSECUTIVE YEARS (1990/1991) WITH THE GENERALIZED SOIL INVENTORY FOR THE R.M. OF HALDIMAND-NORFOLK.

Soil Associations (Scale 1:100,000)[†]		1990/1991 Corn Area by Local Municipality (ha)		
Mode of Soil Deposition	Corresponding Soil Series Names (from 1:25,000 Scale Mapping)	Township of Norfolk	Township of Delhi	City of Nanticoke
*Mainly lacustrine silty clay	Brantford, Beverly, Toledo	38 (15%)[‡]	78 (40%)	748 (26%)
Mainly lacustrine heavy clay	Smithville, Haldimand, Lincoln	—	—	462 (15%)
*Mainly silty clay loam till	Muriel, Gobles, Kelvin	532 (32%)	298 (57%)	—
*Mainly lacustrine silt loam	Brant, Tuscola, Colwood	375 (44%)	156 (39%)	404 (45%)
40-100 cm of sandy or loamy sediments over lacustrine clays or loams	Brookton, Berrien, Wauseon, Walsher, Vittoria, Silver Hill, Tavistock, Maplewood	553 (43%)	406 (52%)	519 (33%)
Mainly lacustrine sands with wind-modified surfaces	Fox, Brady, Granby, Wattford, Normandale, St. Williams, Lowbanks	990 (52%)	1190 (45%)	415 (42%)
Mainly eolian sands at least 100 cm thick, often duned	Plainfield, Walsingham, Waterin	1605 (45%)	657 (42%)	60 (35%)
Gravelly sands of fluvial or till derivation, or 40 to 100 cm of sandy sediments over gravelly sands	Burford, Wilsonville, Scotland, Oakland, Vanessa	14 (3%)	340 (48%)	170 (39%)
	Landsat TM Classified Image Area Total for 1990/1991 Corn (Hectares):-	4107	3125	2778
	1990/1991 Corn Area as a Percent of Local Municipality Area that Is Cleared and Available for Agriculture:-	9.7%	8.7%	5.6%

[†]after L.R.R.I. (1985) and Presant and Acton (1984)
[‡]the number in brackets is the proportion (expressed as a %) of continuous corn area to corn in rotation with other common field crops (by soil association and local municipality)
*soil associations most susceptible to compaction (McBride, 1994; Veenhof and McBride, 1996)

corn was grown for two consecutive years. In virtually all instances, the area totals for continuous corn were less than half of the area totals for corn grown in 1991 only, whether totaled by local municipality or by soil association within a local municipality. The area total for the three municipalities is about 2600 ha, or about 2 percent of the area that is under arable culture. The evidence of corn in rotation with other crops was strongest in the local municipality of Nanticoke, where the decline in corn area grown for two successive years on the same land in relation to the 1991 corn area total was generally three-fold or greater. Plate 2 shows that the dominant rotation is with soybeans in this central part of the region where medium-textured soils dominate. There appears to be a greater tendency toward continuous corn cropping systems on the Norfolk sand plain where alternative crops to tobacco (including corn) are being introduced (Table 5, Plate 2).

Table 5 includes information on the proportion of the total area of continuous corn in 1990/91 in relation to the area of corn in rotation with other common field crops by soil association and by local municipality. These percentages range from 3 percent (droughty gravelly sands in Norfolk) to 57 percent (compactible silty clay loam tills in Delhi), but generally amount to one-third to one-half of the area for most soil associations in these local municipalities, including the three soil associations that are most prone to compaction.

Conclusions

This case study has demonstrated the usefulness of an integrated image analysis-GIS approach in successfully identifying land areas that are highly susceptible to tillage- and traffic-induced soil compaction during crop planting and harvesting periods, given their present use for row crop production (including continuous corn) and their measured or estimated compression behavior. Census data (five year periodicity) cannot provide the field level information on annual cropping patterns and rotations needed for this purpose. This study was not aimed at mapping the current state of soil overconsolidation in the region, but only the potential risk of further damage from mechanized field operations in relation to the current baseline condition.

In general, the map units that depict the coincidence of continuous corn cropping systems and medium-textured soils vulnerable to compaction are sparsely distributed across the region and do not point to well defined localities of concern. Analysis of the area cross-tabulation reports, however, suggests that the silty clay loam tills may be particularly at risk. There is therefore some basis for concern that the practice of continuous corn monoculturing is contributing significantly to an escalation in compaction risk on the most vulnerable soils in this regional municipality.

A number of aspects of this study approach were identified which require further investigation in order to improve its usefulness in soil conservation planning. These areas for further research include determining (1) the minimum level of effort required for a prescribed user's accuracy level in collecting reference data for the training stage in crop identification from TM imagery, and (2) the impact of cumulative spatial errors on soil degradation risk assessments of this type.

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