An assessment of the degradation of agricultural lands in Canada

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An assessment of the degradation of agricultural lands in Canada

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SUMMARY

Ninety-six percent of Canada's soils in agricultural capability classes one to three are already in production, as is most of the class four land in the more favourable climatic zones. Continued agricultural productivity in Canada is dependent on the maintenance of the quality of these soils, and not on expansion into virgin areas.

Soil quality is not improving markedly over large areas anywhere in Canada. On the contrary, many soils across the country are deteriorating as a consequence of one or more of the following processes: soil erosion by water or wind; soil structure and fertility loss accompanying intensive tillage; soil salinization; soil acidification; soil contamination by chemical residues; and soil disturbance. In addition, agricultural soils in certain locations are being affected by deterioration of drainage systems and by earthflows or landslides, and organic soils are being permanently lost through oxidation and other factors of subsidence.

Soil erosion by water appears to be a more or less universal phenomenon active in agricultural lands throughout Canada. Principal areas of concern include the potato fields of New Brunswick and Prince Edward Island, the intensively farmed clay soils of Quebec and Ontario, and the summerfallowed slopes of the Peace River districts of Alberta and British Columbia. Wind erosion, still a major concern on the prairies, also occurs in the sandy soils of Ontario and even in the Atlantic provinces, wherever large areas are tilled.

Soil deterioration is occurring as a result of intensive tillage, resulting in the loss of organic matter. Associated with this deterioration are reductions in soil fertility and breakdown of structure. Working soils when wet also damages soil structure. Such problems can be found across the country. They tend to be most serious in sandy soils where excessive tillage in dry conditions reduces fertility, and in clay soils where tillage in wet conditions causes compaction. Summerfallow in the prairies and row-crop tillage in the east and in British Columbia seem to be the chief causes of soil fertility loss and structure deterioration in those areas.

Soil salinization is a problem in western Canada, associated with summerfallow and altered vegetation patterns which have led to the movement of salt-laden subsurface water to the surfaces of seep areas. It appears to be growing steadily in area and is difficult to arrest. It is probably the principal soil quality concern in the prairies. By contrast, acidification is mainly a problem in eastern Canada, resulting from the acceleration of natural soil leaching processes by additions of acid in precipitation and from nitrogen fertilizers, with the latter being the dominant process. Acidification need not be of great concern if lime is used at adequate rates.

When soils are used for the disposal of wastes, such as sewage effluent or sludge, there is the risk of contamination by heavy metals and organic toxicants which are often present in such wastes.

Pesticide residues and airborne contaminants may also accumulate in soils. While not yet a problem of major proportions, soil contamination is of concern especially in the more densely populated parts of Canada where soils are valuable and wastes are generated in the greatest quantities. Once contaminated, a soil may be reduced in value for crop production for an extended period.

Other soil quality problems, such as mixing, disturbance, earthflows, landslides, deterioration of drainage systems, and subsidence of organic soils, are local in extent. They may occur anywhere in the country where the necessary conditions exist.

On the whole, little is currently being undertaken by way of preventative or ameliorative measures. Certain specific practices can be identified, especially where problems have been recognized for some time. Nationally, soil quality problems tend not to be considered as a significant factor in long-term agricultural productivity. Until they are, they will not receive the attention they deserve.

ACKNOWLEDGEMENTS

A great many people have contributed to this report, either directly or by way of commentary during visits of the senior author to different parts of the country. To list them all individually would be difficult and any inadvertent omissions would be regrettable. The authors therefore wish to extend their appreciation for the time and assistance provided collectively by individuals on the staff of all the federal-provincial soil survey units and the provincial ministries and departments of agriculture. Scientists at Agriculture Canada's research stations also gave much time in assisting with this assessment. Special thanks are extended to those at Charlottetown, Fredericton, Harrow, Swift Current, Lethbridge, Beaverlodge and Summerland research stations, and the Vegreville Substation. Various staff of the Land Resource Research Institute in Ottawa also provided information for this report, which is gratefully acknowledged.

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1. INTRODUCTION

1.1 Objectives and Approach

This monograph presents a general qualitative assessment of the kind, location and extent of land degradation in the agricultural regions of Canada. In so doing it establishes an information base from which to consider research needs and priorities related to the quantitative assessment of soil deterioration across the country and the development of land management techniques for combatting it. "Land degradation" is considered to be the process or processes of deterioration of soil edaphic qualities relative to their natural or most productive previous state.

Studies related to land degradation have tended to be specialized, depending on the interests and skills of individual researchers. In 1968, the national Soil Fertility Committee conducted a symposium on soil pollution (21). In 1971 a special report on soil conservation and pollution concerns was prepared for the Interdepartmental Committee on International Environmental Activities (23). In the same year, a valuable contribution was made on a global scale with the publication of the FAO bulletin Land Degradation (89). The above documents, however, were not geographically based and thus fell short of meeting current information requirements. This review has been prepared in an attempt to fill this need.

The approach to problem identification used in the following pages is similar, in principle, to that of FAO (89). The scope has been expanded, however, to include the range of natural and man-induced processes which are relevant in Canada at this time.*

1.2 Land Degradation in Perspective

Land degradation is a concern in Canada from a number of points of view, all of which centre on the need to conserve the land resource for agricultural production. Nearly one-half of Canada's total land area is located in arctic or sub-arctic climatic zones, with essentially no agricultural potential, and a further 25% is in cold regions where crops and yields are severely limited by temperature (Table 1). Approximately 12% of the remaining land is semiarid or subarid, where crop growth is limited by available moisture (26). "Improved" farmland in Canada amounts to 44.2 million hectares (4.8% of the total land area). While this is only 54% of capability classes 1 to 4, it is 96% of capability classes 1 to 3. About 20 million additional hectares are considered to hold potential for some form of agricultural use (23), but most of these lie in less favourable climatic zones and are more suited to animal-based agriculture. Where data are available, the proportion of these soils suitable for cultivation has been estimated at only 10% of the total (102).

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* Removing land from agricultural production for urban, recreation, transportation or industrial activities is a political process and thus is not considered in this review.

Table 1. Extent of agricultural lands in Canada (10^6 ha)

Canada - total land area[1]	918.1 (100%)
No agricultural potential - arctic to sub-arctic climate[1]	442.9 (48.2%)
Agricultural potential severely limited by climate, and determined locally by soils[1]	256.6 (28.0%)
i) Cold (soil growing degree days 555-1110)	227.3 (24.8%)
ii) Dry (soil water deficit > 127 mm)	29.3 (3.2%)
Agricultural potential determined primarily by soils[1]	218.6 (23.8%)
Class 1-4 agricultural capability soils [2]	81.7 (8.9%)
Total farmland (1976)[3]	67.2 (7.3%)
Improved farmland (1976)[3]	44.2 (4.8%)
i) Cropped or fallow land (1976)	39.3 (4.3%)
ii) Pasture (1976)	4.9 (0.5%)

1. Reference 26.
2. Reference 102; includes estimate for British Columbia from: B.C. 1978 Agricultural Statistics Yearbook, B.C. Min. of Agric., April 1979.
3. Reference 25.

Table 2 lists a number of factors of agricultural land use which affect the maintenance of agricultural land quality. They suggest that agriculture will be facing an ever-increasing struggle to maintain its present high level of productivity, and that land degradation in the future will be greater than it has been in the past.

Continuing urbanization generates intensification of land use on the remaining agricultural land base. Historically, population centres have developed in areas of Canada with the most favourable climates and soils. The resulting urban expansion creates greater pressure on productive land away from urban centres as more land is removed from agricultural use. Maintaining these lands in the best possible physical and chemical condition is therefore of paramount importance for Canada's future agricultural production.

Another concern is the effect of land degradation on the environment. Table 3 lists some of the more easily recognizable environmental impacts which stem from soil deterioration. The natural landscape, wildlife and fisheries are part of the primary productive land resource.

None of these concepts is new. Concerned individuals and groups have been drawing attention to them for decades. Many of the current problems were described, and some action was taken, in the "dust bowl" years of the 1920's and 1930's. Others have alarmed soil scientists and environmentalists for shorter periods of time.

Many of the processes involved in soil degradation are natural and some would proceed even without man's interference. However, these processes can often be accelerated by the shifting of natural equilibria, or by the inhibition of natural soil-building processes. Soils can be depleted of nutrients and physical stability through exploitation. On the other hand, good management and continued land husbandry such as additions of manure, crop residues, fertilizers and lime, and the maintenance of rotations, can result in lasting improvements to the soil.

It is possible that agriculture's preoccupation and success with increasing productivity has been masking changes in soil quality. Better crop varieties, increased fertilizer use and farm mechanization have all been instrumental in producing a more efficient agricultural industry. However, these improvements have been introduced during an extended period of relatively stable and favourable climate. If weather patterns revert to the variability experienced in previous decades, soil quality problems may become more serious.

1.3 Processes of Land Degradation

Processes which contribute to land degradation can be separated into two broad groups: those which can be observed over a wide area and are the results of regional soil, management and climatic factors, and those which are localized in extent and are functions of local soil or management conditions.

Table 2. Factors of agricultural land use in Canada related to land degradation concerns

The Past 100 years	The next 100 years
1. Improvements in crop varieties, fertilizers and management, giving continual crop yield increases.	1. Yield benefits from variety and fertility improvements reaching a peak.
2. Increasing inputs of inexpensive energy used for tillage, pesticides, fertilizers.	2. Energy costs rising rapidly - some sources discontinued.
3. Heavy reliance on native soil fertility and structure to resist abuse from continued intensive cropping.	3. Soil organic matter levels declining to reach new equilibria with cropping practices - lower fertility and soil structure less able to resist tillage abuse.
4. Marginal land abandoned in favour of better soils and climatic zones.	4. Probable need to return marginal land to agricultural use because of demand for food.
5. Drainage and irrigation developments in areas with greatest benefit/cost ratios.	5. Drainage and irrigation becoming less cost effective as lower-capability soils used.
6. Urban expansion effects absorbed by combination of 1 and 2 above.	6. Land lost to urbanization replaced by lower-capability soils, rather than by increasing yields on better soils.
7. Extensive use of crop rotations under mixed agricultural land use systems.	7. Increased intensification of land use practice under expanding monoculture systems.

Table 3. Potential environmental impacts associated with land degradation

1. Water pollution - surface water;
   - Eutrophication - N, P from erosion and runoff
   - Contamination - pesticides and heavy metals from erosion and runoff.

2. Water pollution - groundwater;
   - Contamination - Nitrate and salts from contaminated soils may move by deep percolation, together with some pesticides and heavy metals if present in the soil in sufficient quantities.

3. Sedimentation - from soil erosion;
   - Wildlife - destruction of fish spawning grounds, filling of ponds, sloughs, etc., which are habitats for many species of wildlife.

4. Air pollution - from wind erosion.

5. Wildlife contamination - from plants and insects contaminated by uptake of pesticides, heavy metals, etc., present in soils.

6. Desertification - from wind erosion, soil contamination.

7. Flooding - from excess runoff, drainage deterioration, sedimentation and landslides.

A listing of regional and local land degradation processes is presented in Table 4. Each of these problems is discussed in the following pages in terms of their development, extent and severity in the major physiographic regions of Canada, which are shown on Map 1. While it is recognized that small parcels of agricultural land can be found in the Yukon and Northwest Territories, in some remote parts of British Columbia and in the Canadian Shield in Ontario and Quebec, lack of information precludes a discussion of these areas.

The discussion and maps presented in the following pages apply chiefly to areas of "improved" agricultural land. Thus, areas of unimproved land such as woodland, rangeland, and residential, recreation and utility lands, while often included within the agricultural zone, are not necessarily subject to the same degradation processes as the improved, or actively managed, farmland. Map 1 shows the approximate boundary of agricultural land use, and indicates the extent of improved land on farms within this area. Farmland has a wide range of use intensities.

2.0 SOIL EROSION BY WATER

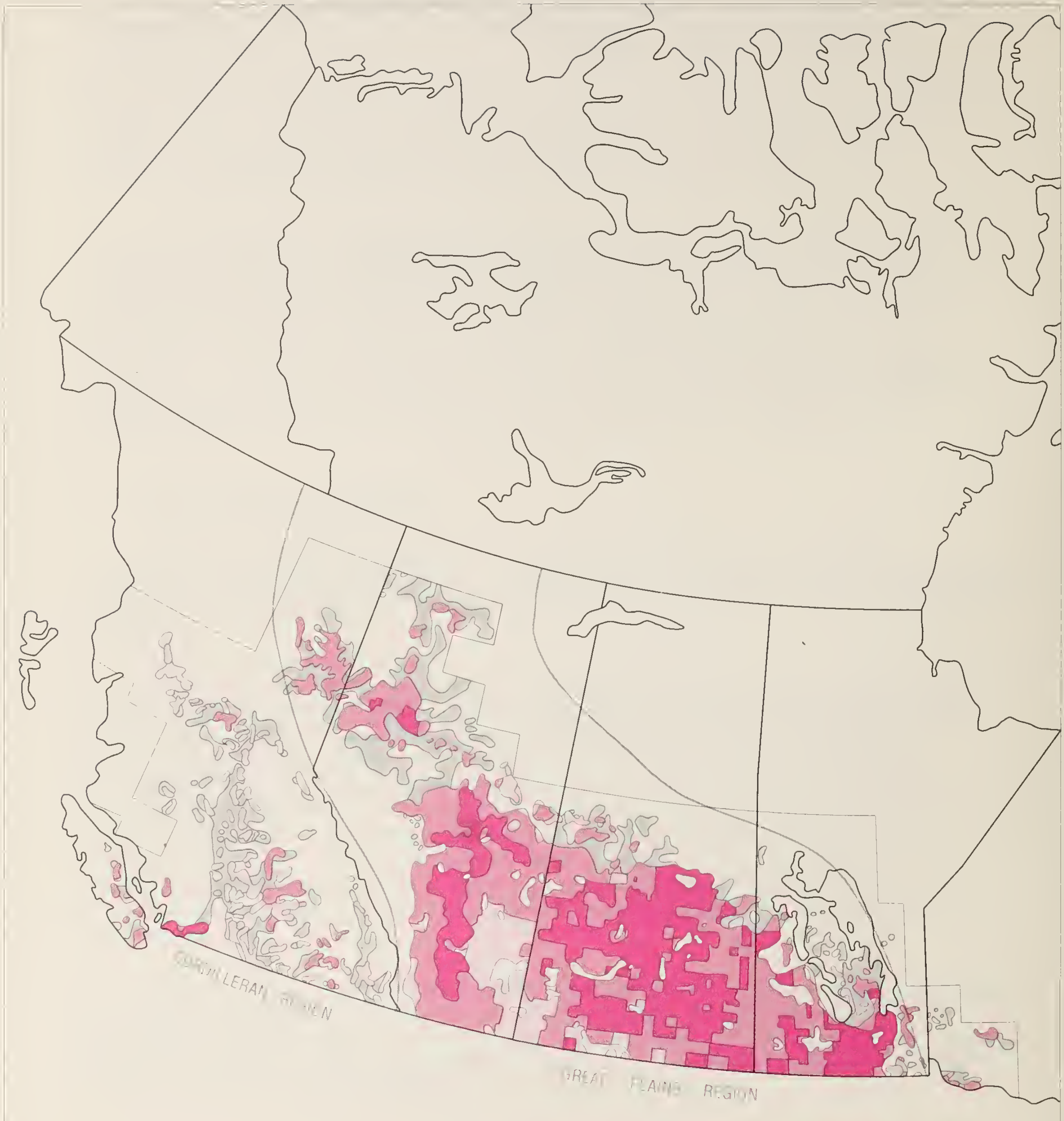
Erosion by water is the most widespread and most frequently recognized manifestation of soil degradation. It occurs in all provinces, because of land clearing, tillage, snowmelt, rainfall or their combined effects.

Soil erosion by water moves or removes nutrients needed for crop growth. It causes sorting and redistribution of soil particles, often resulting in the removal of organic matter and the very fine grained mineral fractions. These are the most valuable soil constituents, having the greatest cation exchange capacity and quantity of adsorbed nutrients. Soil erosion often leaves parts of fields with shallow topsoils and sola, resulting in reduced water-holding capacity and root development, and leading to uneven crop growth. It also results in siltation of natural surface drainage routes, which causes smothering of seedlings in spring and crusting of surfaces when the deposited soil dries out.

Soil erosion causes environmental concerns of considerable magnitude. The eroded particles transport pollutants, such as phosphorus and the persistent pesticides, by absorption, to streams, rivers and lakes. The sediment itself is also damaging to aquatic environments where it reduces light penetration and blankets fish spawning grounds.

The main factors determining the rate and extent of soil erosion by water are: i) the soil's resistance to disaggregation by raindrops or running water, which is a function of particle size distribution, organic matter content, permeability, degree of aggregation and structural stability; ii) the intensity of rainfall or runoff events; iii) the degree and length of slope, which determine the amount and rate of runoff concentration; iv) the presence of frozen layers in the soil profile; and v) the vegetation cover or residue which protects the soil from raindrop impact and retards runoff and soil movement.

Map 1: Agricultural Regions Showing 1976 Improved Farmland as Percent of Total Farmland



Map 1: Agricultural Regions Showing 1976 Improved Farmland as Percent of Total Farmland(1)

Cartography compilation and drafting by the Land Resource Research Institute,
Research Branch, Agriculture Canada, *1981*

Area containing improved farmland[2]

- Less than 40 percent of farmland was improved land in 1976
- 40-74.9 percent of farmland was improved land in 1976
- 75 percent or more of farmland was improved land in 1976

Area possessing some capability for agriculture, but not farmed in 1976[3]

Canada Land Inventory Boundary

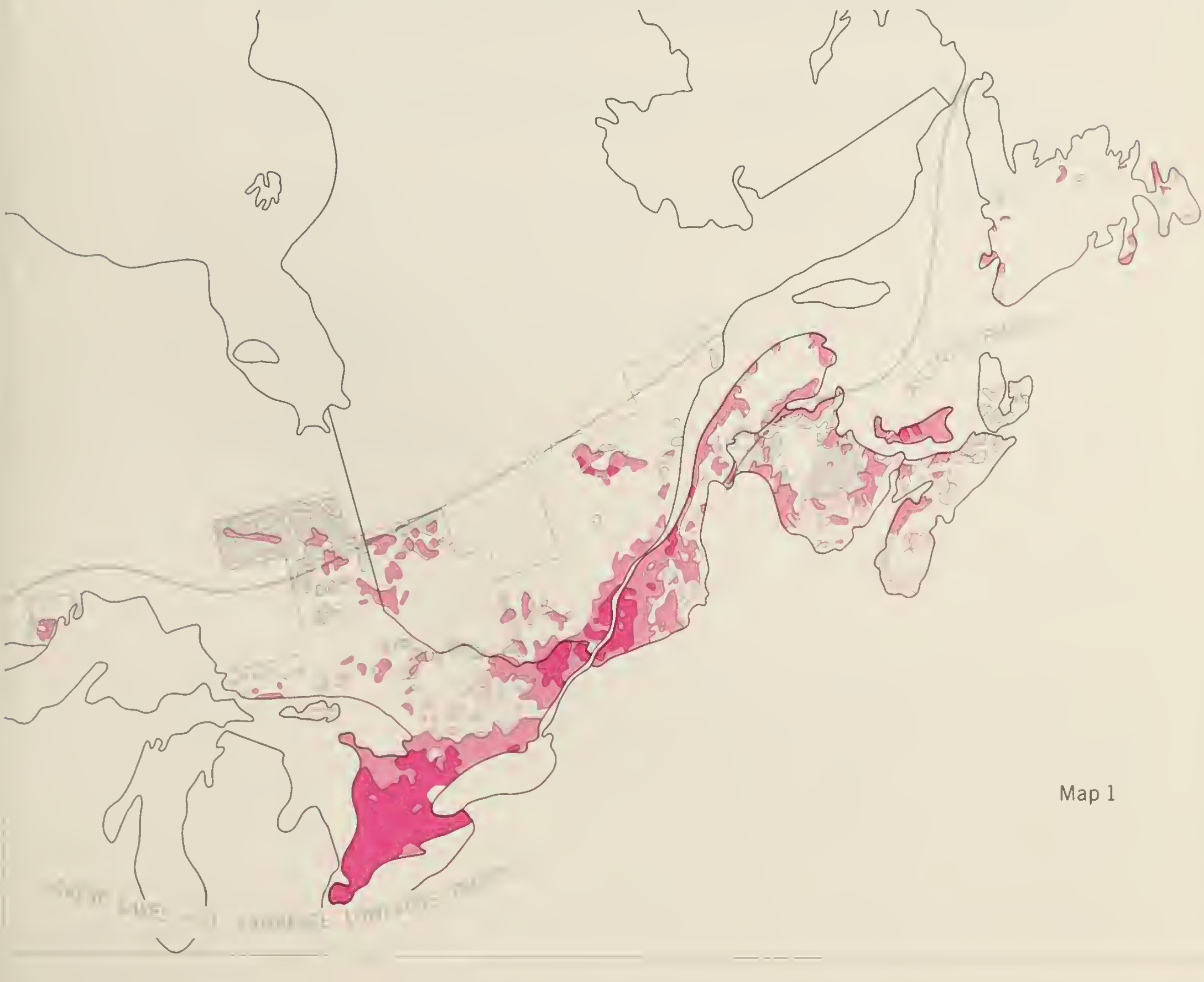
Boundary of Agricultural Regions[4]

(1) From map based on 1976 Census of Agriculture, prepared by Statistics Canada, Geocartographic Group, Ottawa. Improved farmland includes land occupied by farm buildings etc., and all land which has recently received chemical or physical ameliorative modifications.

(2) From 1:7.5 million map based on Land Use, Canada Land Inventory, prepared by C. Gosson, National Atlas of Canada, Energy Mines and Resources Canada, Ottawa, 1980.

(3) From 1:7.5 million map based on Soil Capability for Agriculture, Canada Land Inventory, prepared by C. Gosson, National Atlas of Canada, Energy Mines and Resources Canada, Ottawa, 1980.

(4) Modified from: Clayton, J.C.; Ehrlich, W.A.; Cann, D.B.; Day, J.H.; Marshall, I.B. 1977. Soils of Canada, Vol. I, Agriculture Canada, Ottawa; Great Lakes – St. Lawrence Region includes some agricultural areas in the Canadian Shield and Appalatian physiographic regions.



Map 1

Table 4. Land degradation processes

1. Regional

    i) Soil erosion by water, including sheet, rill and gully erosion

    ii) Soil erosion by wind

    iii) Soil structure and organic matter loss due to cultivation

    iv) Soil salinization caused by both dryland seeps and irrigation water, including localized alkalinization

    v) Soil acidification from fertilizer use and atmospheric sources of sulfur and nitrogen

2. Local

    i) Soil contamination from pesticides, waste-water sludges, atmospheric pollution

    ii) Soil disturbance and mixing by surface-access mining, pipeline installation, etc.

    iii) Subsidence of organic soils by oxidation, shrinkage and erosion

    iv) Earthflows and landslides

    v) Flooding, waterlogging and deterioration of drainage systems

The relative water erosion risk across Canada is shown on Map 2. This map is based on the expected annual flow of water to streams, the maximum 1-hour rainfall in a 10-year return period, and surface soil texture. These factors indicate the recurring seasonal excess of precipitation or snowmelt over soil moisture storage capacity, the risk of infrequent high-intensity storms, and approximate soil infiltration rates and erodibilities, respectively.

The distribution and intensity of cropping practices, representing soil disturbance and the vegetative cover available to protect soils from erosion, are used to modify the risk assessment shown on Map 2. This information is presented on Map 3, which indicates the degree and extent of water erosion currently occurring. Map 3 correlates well with reported soil erosion problems, and therefore provides a reasonable overview of the national situation.

2.1 The Cordilleran Region

Two severe but different water erosion problems are found in the mountainous western area. The first occurs in the cultivated soils of some river valleys where tillage practices leave soils unprotected against erosion by heavy rains and runoff. The second occurs in the forested regions during and after logging. The latter kind of erosion is beyond the scope of this review, but it is a serious problem and deserves attention. It sometimes affects agriculture directly by silting streams and degrading water for irrigation purposes, and often occurs on land that has potential for agricultural use in the future.

Soil erosion by water is a recognized problem in the lower Fraser valley and to a lesser extent in parts of the Okanagan and Kootenay valleys, where intensive cultivation for wide-row crops such as corn, potatoes and grapes is practiced. Rainfall occurs mainly during the winter months, contributing to the erosion of cultivated soils left bare of vegetation over winter. In the interior valleys, precipitation is generally low and irrigation is necessary for most crop production. Many of the soils have developed on silty lacustrine materials, and are highly erodible under cultivation and irrigation. Applications of irrigation water are sometimes the cause of piping and slumping in these soils.[1] At present no quantitative data exist to determine the rates of soil loss occurring in the cultivated soils of valleys in British Columbia.

Erosion problems in these cultivated soils are not likely to diminish, as trends indicate more intensive cropping, especially in the lower mainland (24, 25). Zero and minimum tillage practices may hold some potential for reducing soil erosion, but are not used to any extent. Better control of irrigation applications, and the greater use of sprinkler and drip systems rather than surface distribution, may further reduce erosion of irrigated soils. Grass ground cover essentially eliminates water erosion in orchards, but in vineyards clean cultivation is commonly practiced and irrigation, snowmelt and rainfall occasionally cause erosion.

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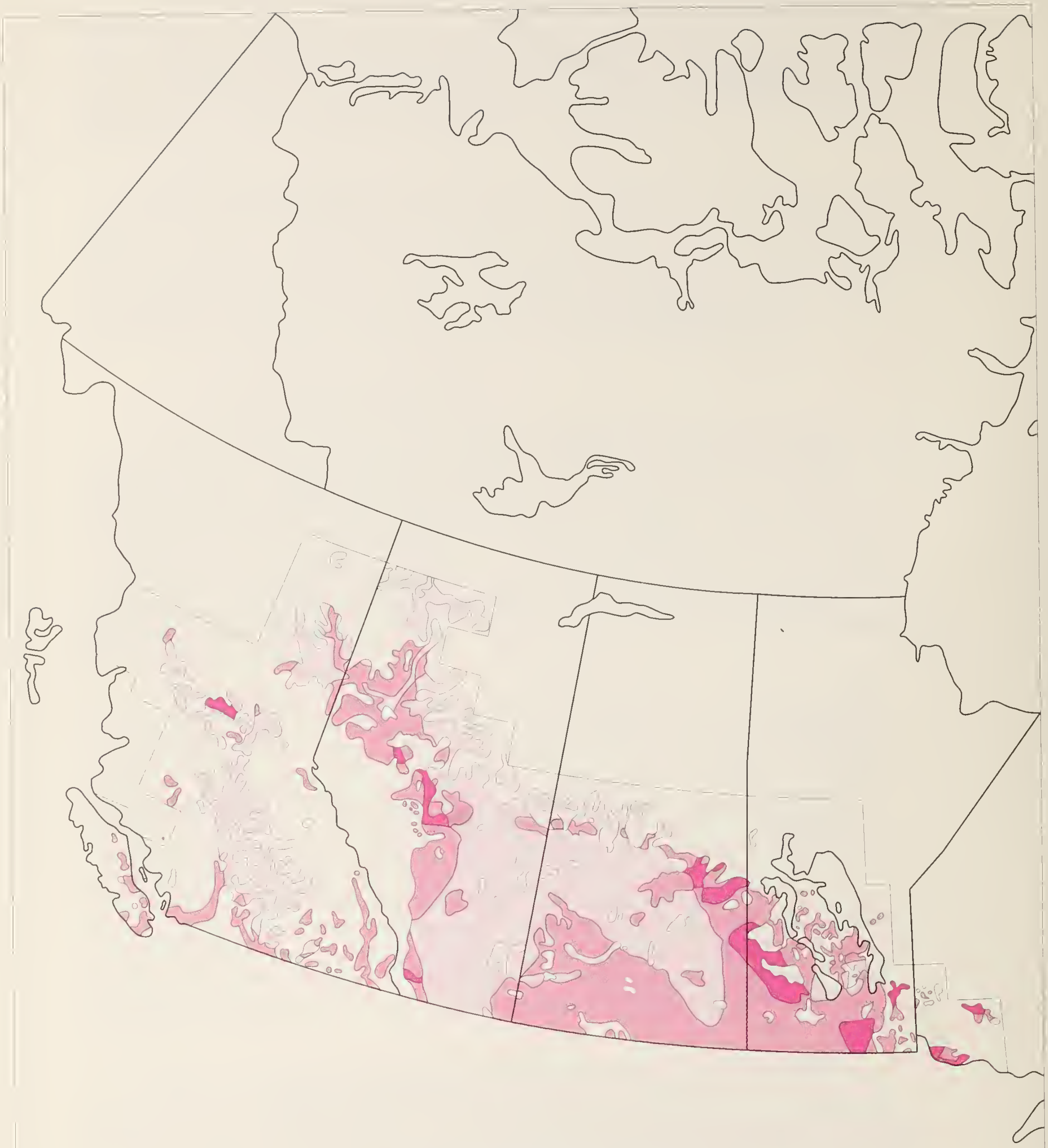
[1] Piping is the process of underwashing, which results in eroded tunnels and occasional collapse features.

Map 2: Relative Water Erosion Risk

Map 3: Relative Water Erosion Risk Modified by 1976 Cropping Practices



Map 2: Relative Water Erosion Risk

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Low; see table below

Moderate; see table below

High; see table below

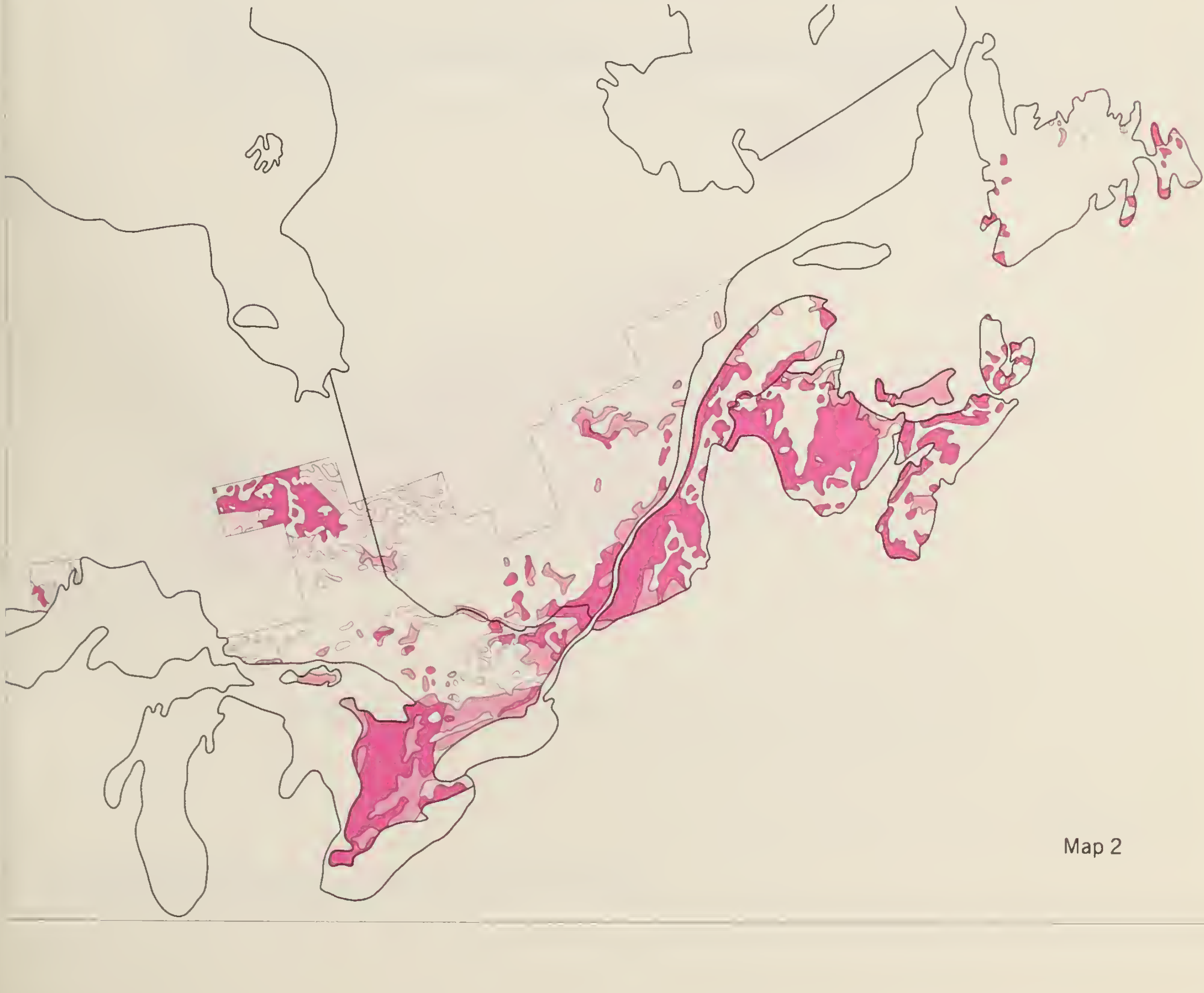
Surface Soil Texture[1]	Mean Annual Runoff (mm)[2] <100				100-500				>500			
	10 Year–60 min. Rainfall (mm)[3]											
	<24	24–<40	40–<56	≥56	<24	24–<40	40–<56	≥56	<24	24–<40	40–<56	≥56[4]
Sandy	Low	Low	Low	Moderate	Low	Low	Moderate	Moderate	Low	Moderate	High	Not Applic-able
Loamy	Low	Low	Moderate	Moderate	Low	Moderate	High	High	Low	High	High	Not Applic-able
Clayey	Low	Moderate	Moderate	High	Moderate	High	High	High	High	High	High	Not Applic-able

(1) Based on published and unpublished soil survey data.

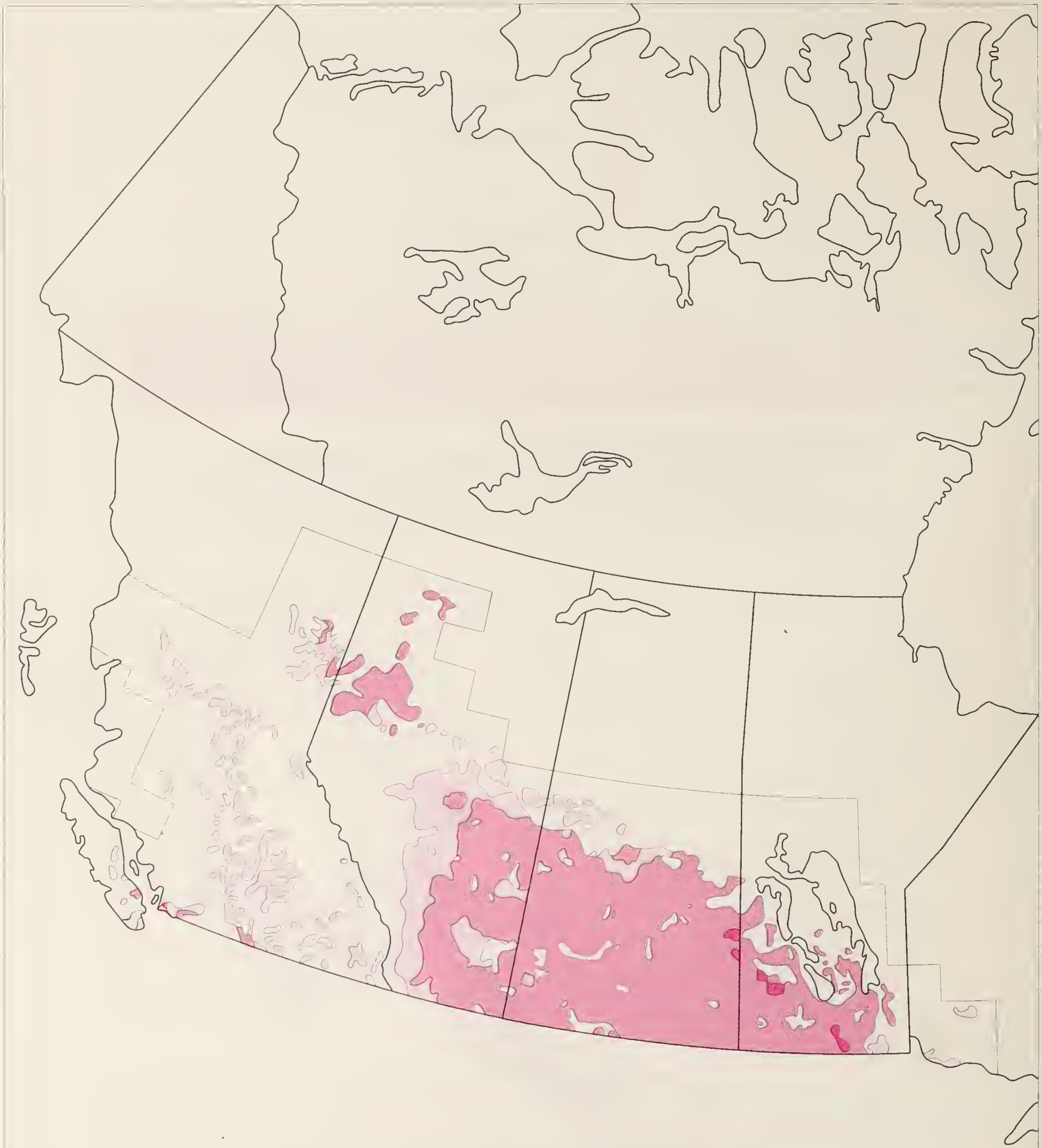
(2) From: Annual Runoff (mean annual unit-area water yield to stream channels); Hydrologic Atlas of Canada, Fisheries and Environment Canada, 1978.

(3) From: Depth, Duration and Frequency of Point Rainfall; Hydrologic Atlas of Canada, Fisheries and Environment Canada, 1978.

(4) Rainfall intensities greater than 56 mm. in 60 min. do not occur in runoff zones greater than 500 mm.



Map 2



Map 3: Relative Water Erosion Risk Modified by 1976 Cropping Practices

Cartography compilation and drafting by the Land Resource Research Institute,
Research Branch, Agriculture Canada, 1981.

Low; see table below

Moderate; see table below

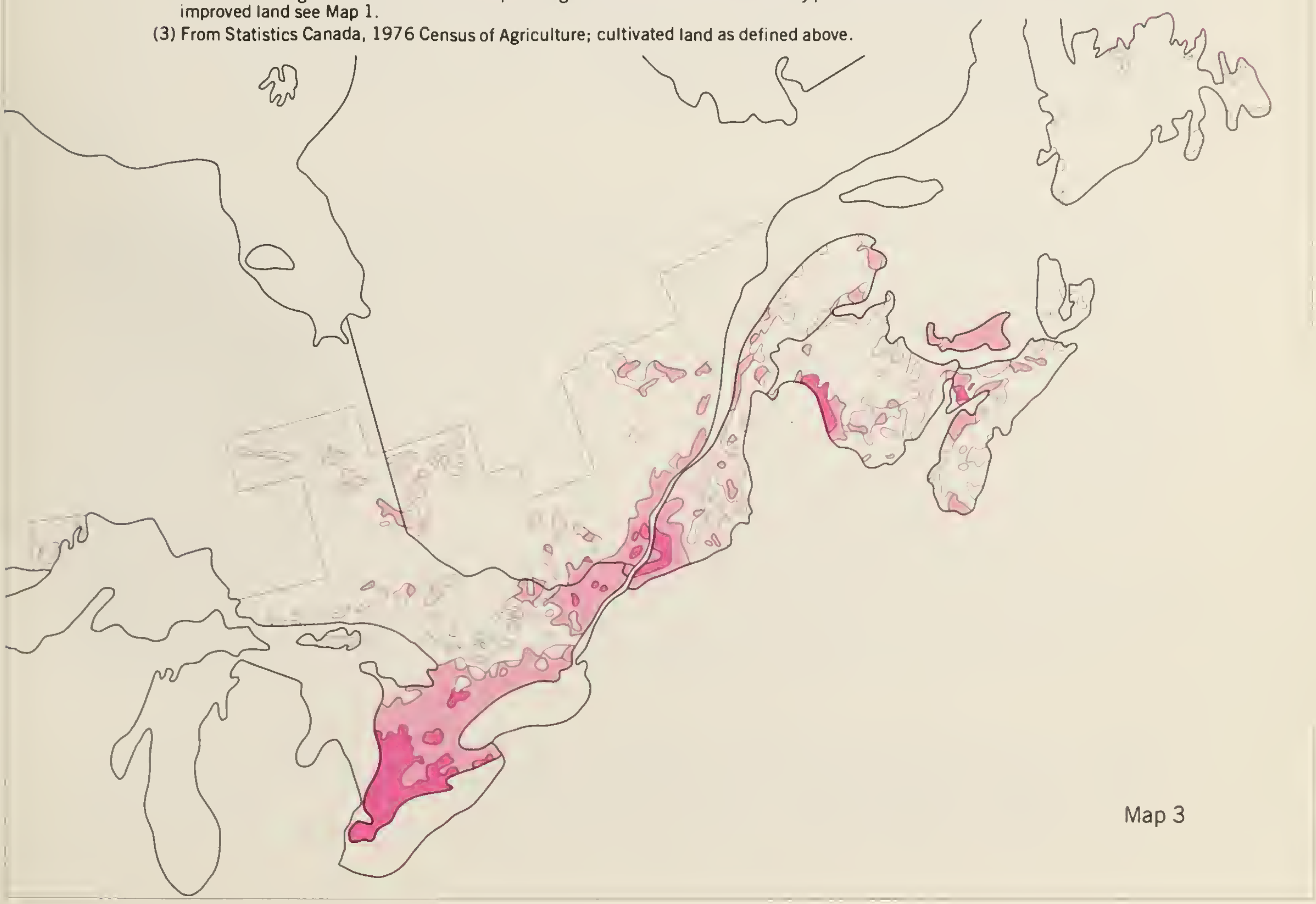
High; see table below

Relative Water Erosion Risk(1)	Cultivated Land (% of improved land)(2)	Row Crops (% of improved land)(2): 10			10-25			25		
		Summerfallow (% of cultivated land)(3): <30	30–40	>40	<30	30–40	>40	<30	30–40	>40
Low	<30	Low	Low	Low	Low	Low	Low	Low	Not Applicable	
	30–75	Low	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	>75	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Moderate	<30	Low	Low	Low	Low	Low	Moderate	Moderate	Not Applicable	
	30–75	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	High	High
	>75	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	High
High	<30	Low	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Not Applicable	
	30–75	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	High	High
	>75	Moderate	Moderate	High	High	High	High	High	High	High

(1) From Map 2.

(2) From Statistics Canada, 1976 Census of Agriculture; cultivated land = land under crops − total tame hay + summerfallow; row crops = field peas + field beans + corn for grain + corn for ensilage + soybeans + sunflowers + potatoes + tobacco + sugar beets + other field crops + vegetables + small fruit + nursery products. For a definition of improved land see Map 1.

(3) From Statistics Canada, 1976 Census of Agriculture; cultivated land as defined above.



Map 3

Water erosion is sometimes caused by recreation and exploration vehicles destroying the fragile grass cover in the arid interior plateau region. This gives rise to gully formation during the snowmelt period and after heavy rains. Piping and slumping in silty terrace soils in many of the interior valleys also result from water concentration from highways, rooftops and septic tanks, as well as from irrigation.

2.2 The Great Plains Region

Soil erosion by water is associated with annual rainfall and snowmelt runoff in the moister extremities of the agricultural area of the Great Plains, particularly in the lower foothills of Alberta, the Peace River district, the Gray Luvisolic soil zone, and the southern Manitoba floodplains. Elsewhere in this region soil erosion by water is generally an intermittent problem associated with infrequent severe rainfalls. These short-lived phenomena cause localized damage to knolls and sloping fields, and often result in soil movement over relatively short distances, usually within a single field.

Recurrent erosion caused by annual snowmelt and runoff occurs extensively within the Peace River district. The soils of this region commonly have erosion-susceptible, fine textured surface horizons and slowly permeable subsurface horizons. Extensive land clearing in the upper reaches of stream catchments creates problems as existing channels often have insufficient capacity to handle the greater runoff, especially in the spring. When soil erosion leads to sediment deposition in stream channels, stream capacities are further reduced. Flooding and gullying in fields bordering streams are a frequent problem, as is erosion caused by uncontrolled discharge of runoff from road ditches, particularly around culverts.

Summerfallow has been shown to lose four to eight times more soil during snowmelt conditions than stubble land (78). While summerfallow tends to be less widely used in the Peace River district than elsewhere in the Prairie region, it contributes to the soil erosion problem nevertheless. Erosion control measures such as grassed waterways and contour or strip cultivation are rarely applied, and little use is made of adequate runoff control structures such as drop inlets and check dams to prevent gullying in existing channels. The Peace River and its tributaries are deeply incised into the plateau, which makes it difficult to control runoff in the channels. To date few control measures have been used, with the result that natural erosion has been accelerated by the greater flows resulting from land clearing. The Alberta Environmental Conservation Authority has recognized this district as an area especially susceptible to erosion and one where agricultural practices and land use and water management systems specifically suited to the area are needed (119).

Similar conditions exist in the Black Chernozemic and Grey Luvisolic soil zones of the lower foothills of Alberta and the northeastern part of this region. In the lower foothills area, environmental agencies are concerned about land clearing, grazing and cultivation adjacent to streams, which may result in sediment deposition and degradation of fish habitat. In Saskatchewan, cooperative watershed projects were initiated in 1956, mostly in the Carrot River and other drainage basins in the Prince Albert - Tisdale region, and in the upper Assiniboine basin in the Yorkton - Kamsack area. Through these projects, funding and assistance have been provided to stabilize channels and establish grassed waterways, contour cropping, legume rotations and other control measures (49). Similar soil erosion problems are also noticeable around the Duck and Riding Mountain areas of Manitoba (54). In the Tiger and Pembina Hills and Turtle Mountain areas of southern Manitoba and in the Red River valley, water erosion is further influenced by generally higher intensities of storms, resulting in extensive soil degradation (53).

The infrequent intense summer storms occurring in the low-rainfall areas of the Interior Plains are a significant cause of local water erosion. The problem is characterized by local sheet erosion of knolls, and rilling and gullying near road culverts. The greatest effects are observed in the southern part of the region where rainfall intensities are highest and where there is the greatest use of summerfallow. Storms tend to be localized and brief, and seldom occur in the same place in two consecutive years. Few data are available to predict these events, and thus management practices tend to ignore them. However, erosion can be severe when they do occur. In a study near Edmonton (117), over 4 t/ha of soil were lost in less than 1 hour compared with a 10-year average annual loss of 2 t/ha on summerfallowed plots. The erosion from summerfallow averaged more than twice that from wheat in a wheat-fallow system, and 40 times more than wheat in a 5-year rotation with oats, barley and hay.

Most irrigation in the region takes place in organized districts in southern Alberta, with a smaller area in Saskatchewan. Small irrigation projects are scattered throughout southern Saskatchewan, many of them for hay or pasture. Poor water application practices have eroded some fields, but more significant are instances of poor management of return flows and unused irrigation water. This water often receives minimal attention resulting in haphazard discharge into streams and ditches, which causes gully and bank erosion, and subsequent stream siltation and degradation.

2.3 The Great Lakes - St. Lawrence Region

The association of stream sediments with phosphorus transport to the Great Lakes has recently led to an extensive study of soil erosion and sediment movement in relation to agricultural practices (122). Estimates of the contribution of agricultural activities to stream sediment loads have been made, the areas have been mapped and remedial options have been discussed and compared. As a result, there is probably better information on this subject in Ontario than elsewhere in Canada.

Soil erosion in Ontario was not generally severe until the area used for corn and other row crops started to increase in the 1960's. Consequently, erosion control programs are not well established. With current trends in cropping practices and the new emphasis on water quality, this situation is changing. A new incentives grants program in Ontario now permits a limited degree of funding assistance for erosion control.

The long-term shift to the production of corn and soybeans at the expense of hay and small-grains crops is continuing across the entire agricultural portion of the Great Lakes - St. Lawrence region as new varieties suited to the available heat units of the cooler areas are made available. Fall plowing is extensively practiced in these areas to avoid spring seeding delays. Fencerows have been removed, and woodlots and densely vegetated areas around streams have been cleared and cultivated to facilitate the use of large machinery. Erodible fine and medium textured soils with inadequate protective cover are being exposed to raindrop impact and snowmelt runoff.

In areas of highest potential erosion in southern Ontario, where rainfall energy and soil erodibility are greatest, soil under continuous corn on fairly level land is estimated (122) to erode at rates up to about 12 t/ha annually, while corn in rotation with hay is not expected to exceed about 7 t/ha per year. Pasture generally erodes at less than 1 t/ha per year. In a field study in southwestern Ontario, continuous corn on a 7% slope had an average soil loss of 19 t/ha annually over a 10-year period. In rotation with hay and oats, annual losses from the corn crop were only just over 1 t/ha (60). In a field study in eastern Ontario, continuous corn grown up and down a 10% slope on a clay soil with low permeability resulted in average annual soil losses over a 12-year period of 49 t/ha. When the corn crop was grown in a rotation, manured and planted on the contour, erosion was reduced slightly but still averaged 31 t/ha per year (93).

The significance of these high erosion rates to water quality depends on the degree of transmission of the eroded soil material to streams. This "delivery ratio" has been found to range from about 10% to 30% (122). Most sediment is delivered to streams in February, March and April. Water quality problems are compounded by the extensive network of municipal drainage ditches, which provide individual farmers with improved drainage outlets but also act as conduits for eroded soil. They often erode and slump, contributing further to stream sedimentation problems.

Soil erosion is perceived differently in Ontario by those concerned with agricultural production and those concerned with water quality. From the standpoint of agricultural productivity, predicted average rates of soil erosion have not been considered extreme by comparison with accepted sustainable losses established for the USA (128). This is primarily due to the relatively low erosivity of Ontario rainfalls compared with those in the eastern United States. One study has suggested that the effect of erosion on corn yields was too small to justify control measures (60). Nevertheless, erosion rates are high, in view of Canadian conditions and the relatively shallow Canadian soils. The productivity of individual fields or parts of fields may be seriously threatened if improved management practices (such as contour and minimum tillage, spring plowing, seeding a winter cover crop, and the use of crop rotations) are not soon established. This is of special concern where continuous wide-row crops (corn, beans, potatoes) are grown (57).

From the perspective of water quality, the fine textured materials eroded from heavily fertilized fields adjacent to streams and ditches contribute to phosphorus pollution of streams and lakes. In some cases, pesticides and other contaminants are also transported along with phosphorus and, together, these pollutants are degrading fresh water streams and the Great Lakes. It has been estimated that about 26% of the total phosphorus and 60% of the "non-point" phosphorus loadings to the Great Lakes from the Canadian side of the basin can be attributed to agriculture, and this occurs primarily through soil erosion (29). In this context, remedial measures are needed which prevent eroded soil from entering streams, especially the very easily transported clay fraction. Reduction of erosion rates by improved management is unlikely to be sufficient, and other approaches (such as vegetated stream buffer strips and grassed waterways) will be needed, even though they are of minimal economic benefit for crop production.

Quebec agriculture in the St. Lawrence Lowlands has been experiencing changes similar to those seen over the past two decades in Ontario (57). Silage corn in particular has greatly increased, with a coincident reduction in hay and oats (24, 25). The soils concerned are primarily fine textured and nearly level. Little concern exists for the effects of soil erosion on water quality, because drainage flows to the St. Lawrence River and there are few large lakes in the agricultural zones.

Water erosion rates have been measured near Lac Saint-Jean and on the north shore of the St. Lawrence east of Quebec (35, 36). At the Lac Saint-Jean site, average annual erosion varied from less than 1 kg/ha under hay to 56.6 t/ha on a fallowed loam soil graded to a uniform 10% slope. At the north-shore site on a sandy-gravelly loam soil with a slope of 15%, annual soil losses over 10 years ranged from 60 kg/ha under pasture to over 28 t/ha under bare fallow. On potato fields planted across the slope, annual soil losses of only 3.3 t/ha were recorded, while average losses of 6.0 t/ha were observed from potatoes planted up and down the slope. On the average, 41% of the mean annual soil losses from different crops, at this site, occurred during the spring snowmelt period.

Throughout this region a variety of methods could be applied to reduce total erosion. However, excess moisture is a problem, especially in the spring. Drainage improvements have been extensively employed but more are considered necessary in eastern Ontario and Quebec (22). In some respects these are incompatible with reduced soil erosion and sediment transport, particularly on soils with fine texture and low hydraulic conductivity. The two requirements must be carefully reconciled so that improved surface drainage is not achieved at the expense of soil conservation.

Both annual recurrent runoff and intense summer storms contribute to soil erosion in the Great Lakes - St. Lawrence region, especially in southwestern Ontario. In eastern Ontario and eastern Quebec, only a small percentage of the area is cultivated and under row crops, which results in moderate to low erosion overall (Map 3). However, if the trend toward intensification of cash cropping continues, erosion problems will undoubtedly increase substantially.

2.4 The Atlantic Region

The Atlantic provinces have the highest annual rainfall and runoff in Canada, except for the western seaboard and the western slopes of the Rocky Mountains. Problems of soil erosion by water have been recognized throughout the region for many years. In New Brunswick and Prince Edward Island, potato production has long been affected by the problems. More recently, however, the expansion of corn as a silage crop has increased the area of land subject to water erosion. In Newfoundland there is little farmland, and that which exists is primarily used for hay, with only a small area of potatoes, oats and vegetables. Consequently, problems are essentially insignificant compared with the rest of the region, and are associated chiefly with streambank and shoreline erosion.

Field conditions that contribute to soil erosion in the Atlantic region are the undulating to strongly rolling topography, the presence of slowly permeable subsoil horizons in many soils, the high fall and winter precipitation, and the frequent freeze-thaw cycles. The soil in potato areas is generally left in a bare and loose condition after harvest and over winter. Continuous cultivation without the use of rotations is common. In the case of corn the short, wide-spaced stubble left after silage harvest provides little protection for the soil. This results in severe sheet, rill and gully erosion especially during snowmelt and dormant-season storms. Stone removal to facilitate mechanical potato harvesting and fencerow removal to accommodate larger machinery have further increased the problem as infiltration rates have been reduced and the length of sloping fields has been increased. The result is serious soil erosion throughout the region with greatest risk when corn, potatoes and other wide-spaced row crops are grown. Valuable topsoil and nutrients are being lost, and ditches and streams are being choked with sediment. Water quality concerns are not major, however, due to the proximity of the ocean which is the receiving water body for the pollutants in streams and rivers.

Measurements of soil erosion rates have been made in Prince Edward Island on one of the principal cultivated soil types (48). Over a 5-year period (1973-77), measured annual soil losses ranged from 0.2 t/ha on both 7 and 12% slopes under sod to 19.6 t/ha on a 12% slope with potatoes grown up and down the slope. Losses under potatoes grown up and down the slope were about one-half those measured in 1973 and 1974 from fallow soil. Between 1975 and 1977, losses under potatoes grown across the slope averaged approximately one-third of those found with cultivation up and down the slope. Accompanying these soil losses were considerable reductions in organic matter and nutrient contents of the surface soil, which rendered the sites susceptible to greater erosion in subsequent years.

No measured soil loss data are available for New Brunswick, but it has been estimated that cultivated land in this province is eroding at an average annual rate of about 42 t/ha (111). In the potato belt of New Brunswick more than half the soils with agricultural potential have slopes of 5% or more, which is sufficient to lead to soil erosion even under good management. Recent visual estimates indicate that at least one-third of the potato land is severely affected by erosion.

In Nova Scotia the assessment of soil erosion by water is again hampered by lack of data. A small study recently investigated 2 years of soil erosion in a corn field on a 9% slope (63). Measured annual soil loss averaged about 26 t/ha; the actual loss was thought to be considerably higher but this was not shown because of inadequacies in the sampling methodology.

Rotations of small grains with hay have controlled the problem of soil erosion to some degree in Nova Scotia, but in recent years the area of corn grown for silage has greatly increased and so has soil erosion. While the corn area is scattered throughout the province, the crop is grown predominantly on the finer textured, undulating, lowland Podzolic and Luvisolic soils in Hants and Colchester counties. Work has recently been carried out to obtain information on the erodibility of these soils by estimating soil K values (Universal Soil Loss Equation) from texture, organic matter, structure and permeability (11).

The problem of soil erosion in Prince Edward Island has received some study but controls are proving difficult. Soil erodibility values have been determined for the whole province, and encouragement is given to farmers to install grassed waterways, diversions and other control measures, especially where highway runoff spills onto farmland.

An innovation, to establish cover crops, has recently been attempted to protect corn land in Nova Scotia and Prince Edward Island. Aerial seeding of rye, in August or September, has resulted in cover establishment between corn rows. Seeded at this time, rye adequately survives the corn harvesting process and protects the soil over winter. Potatoes, however, are harvested too late in the year to allow establishment of an adequate cover crop, and soil disturbance during harvesting prevents successful cover crop seeding prior to harvesting. Rotations are not readily accepted because of the absence of livestock on many potato farms and the low market value of small grains compared with the value of potatoes.

Structural measures, such as parallel tiled-outlet bench terracing, have been attempted in New Brunswick but have not been generally accepted because of cost, silting and freezing of the outlet area, and the shallowness of many of the sloping soils over the dense glacial-till subsoil (5). More recently, diversion terracing has gained in popularity. Farmers are encouraged to eliminate fallow and to use crop rotations to keep soil covered and increase soil organic matter levels (112, 113).

3.0 SOIL EROSION BY WIND

The regional occurrence of wind erosion is associated with dry conditions, high wind speeds and land use practices that leave the soil unprotected. At the local level, the erodibility of the soil, and the degree to which vegetation and surface roughness reduce wind velocities at the soil surface, determines the rate and extent of wind erosion. Soil components most readily moved by wind are those between 0.02 mm and 0.84 mm in diameter (28). They may be single grained, as in a fine sand or silt, or may be stable aggregates of silt and clay.

Wind erosion is reduced when bare soil surfaces are ridged by cultivation or the surface is left in a cloddy condition, especially when this roughness is oriented across the wind direction. Wind erosion is essentially eliminated by adequate vegetative or trash cover. The distance between areas with this cover, such as between strips in a strip-cropped area or between wind barriers or shelterbelts, determines the susceptibility of bare field blocks to soil drifting (2, 28).

Excessive tillage and drought combine to give the greatest wind erosion hazard, but many soils and management practices, even in the more humid areas of Canada, present conditions when wind erosion can be active at certain times of the year. Organic soils that are drained and cleared are also highly susceptible to wind erosion when they dry out at the surface and have inadequate crop cover.

Soil erosion by wind has received less attention in the past 40 years than it did in the 1920's and 1930's when it was first studied in Canada. This has been due to the improved management practices implemented after the dust bowl period, the return of some of the most susceptible soils to permanent rangelands rather than annual cultivation, and the decrease in the frequency of severe droughts. However, there has been an increasing incidence of wind erosion in almost every province in recent years. Unfortunately, there have been few research studies to document the problem.

The relative wind erosion risk across Canada is shown on Map 4. This map is based on the maximum 1-hour wind speed in a 10-year return period, soil moisture class (obtained from the mean annual soil moisture deficit) which provides an estimate of soil dryness, and surface soil texture which is related to erodibility. On Map 5, the distribution and intensity of cropping practices are used to modify the risk assessment shown on Map 4; Map 5 thus indicates the degree and extent of wind erosion that is currently occurring.

3.1 The Cordilleran Region

Wind erosion does not appear to be a widespread problem in the Cordilleran region, except on some organic soils in the lower Fraser valley used for vegetable production. The eolian origin of some of the soils of the region renders them susceptible to drifting, which can also occur in outwash sands and lacustrine silts when they are exposed and dry. Intensive cultivation in some such soils in the valleys of southern British Columbia has led to intermittent wind erosion and, occasionally, dune formation.

There is concern about the impact of vehicles, especially those used for recreation, in the arid rangelands of the interior plateau. The problem arises from the ease of destruction of vegetation in this fragile ecosystem and from wheel track compaction. The same area is also sensitive to overgrazing, which results in wind erosion in some cases.

3.2 The Great Plains Region

The Brown and Dark Brown soils of the south central and southwestern portion of the Great Plains region were subjected to severe wind erosion during the period from 1920 to 1940. Excessive cultivation, excessive use of summerfallow and unusually low rainfall precipitated a social and economic disaster and a period of tremendous agricultural upheaval (3). Reestablishment of grassland in the most sensitive areas, planting of windbreaks, the acceptance of cross-wind strip cropping, surface residue conservation (which all but eliminated the moldboard plow) and the maintenance of cloddy soils over winter as normal farming practices, together with greater annual precipitation and increased awareness among farmers, eventually improved the situation. A more sustainable farming system has prevailed since that time, but continual vigilance is required. The southern part of the area, from Pincher Creek to Moose Jaw, is the most susceptible, having a combination of frequent high winds and low precipitation (27, 119).

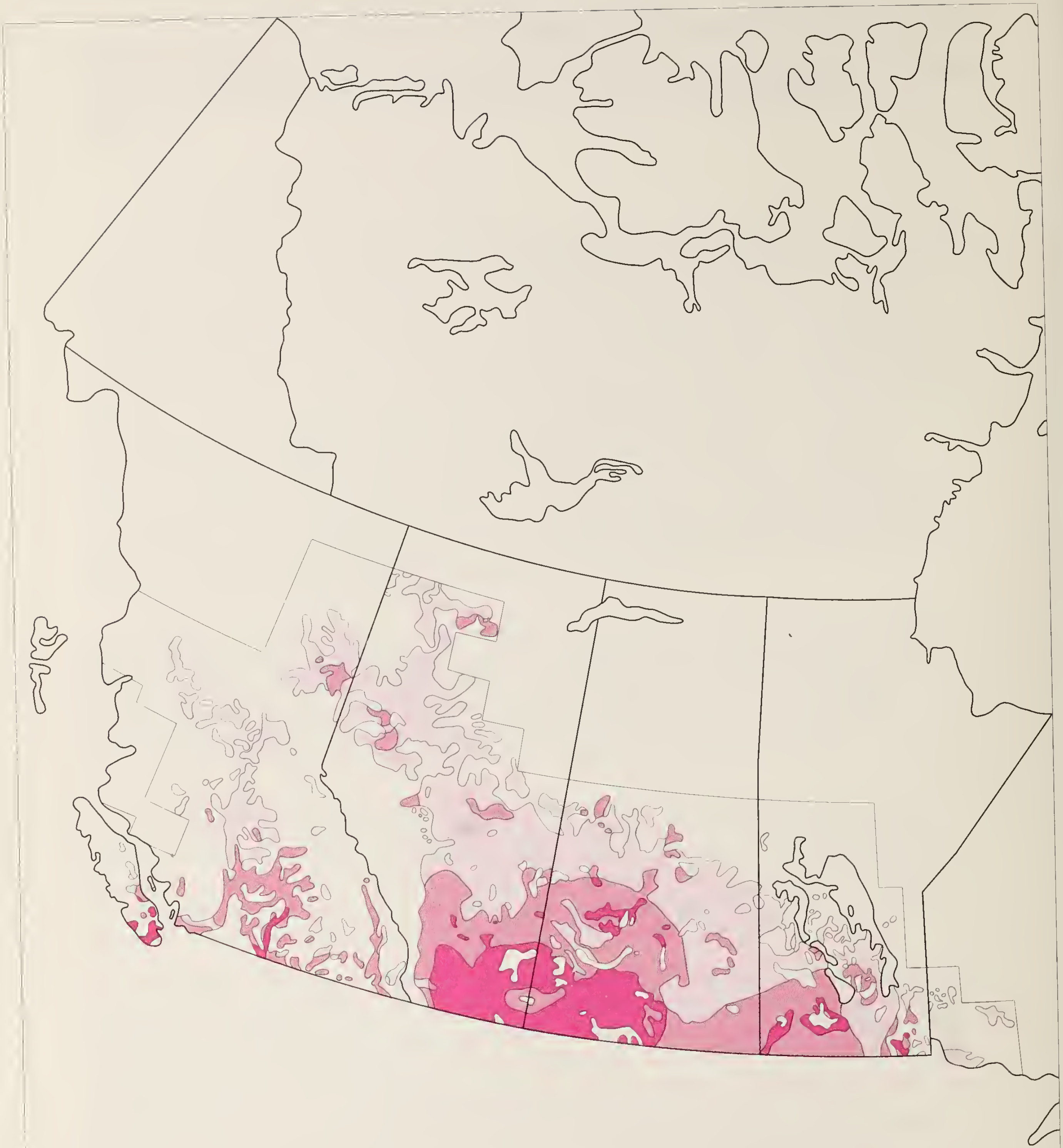
The decades following the worst wind erosion were relatively low-hazard years with adequate rainfall. Farmers became complacent and wind erosion control practices have been neglected (119). Some of the windbreaks that were planted in the early days of reclamation have been removed because of inconvenience and excessive snow accumulation which encouraged salinity in some areas (see section 5.2).

In recent years local problems with wind erosion have reappeared. While no erosion measurements have been made, dust storms have been reported in the southern parts of each of the Prairie Provinces with increasing frequency. The Alberta Soil Conservation Act has been used to require farmers to control wind erosion through emergency measures such as chisel-plowing of frozen ground to arrest soil drifting.

Several factors appear to be encouraging erosion-prone conditions to reappear. Large machinery is most efficient when used in large field units. Strip cropping at the optimum spacing, 25 m in fine sandy loams to 100 m in clay loam soils (2), is less widely used as it is often not compatible with efficient operation of the large equipment that has become popular. Wide machines also tend to "scalp" the knolls, encouraging the initiation of soil drifting. Furthermore, the recent improved economic climate for wheat and rapeseed, together with uncertainty in the beef industry, has encouraged the cultivation of field crops at the expense of forage. At the same time, some marginal lands formerly under permanent grasses have been brought into production. However, economic cycles could reverse these trends.

Map 4: Relative Wind Erosion Risk

Map 5: Relative Wind Erosion Risk Modified by 1976 Cropping Practices



Map 4: Relative Wind Erosion Risk

Cartography compilation and drafting by the Land Resource Research Institute,
Research Branch, Agriculture Canada, *1981*.

- Low; see table below
- Moderate; see table below
- High; see table below

Surface Soil Texture[1]	10 Year Maximum One Hour Wind Speed[2]											
	<80 Km/h				80-100 Km/h				>100 Km/h			
	Soil Moisture Class[3]											
	LM	HK	EFG	CD	LM	HK	EFG	CD	LM	HK	EFG	CD
Clayey	Low	Low	Low	Low	Low	Low	Low	Moderate	Low	Moderate	Moderate	High
Loamy	Low	Low	Low	Moderate	Low	Moderate	Moderate	High	Low	Moderate	High	High
Sandy	Low	Low	Moderate	Moderate	Low	Moderate	High	High	Low	High	High	High

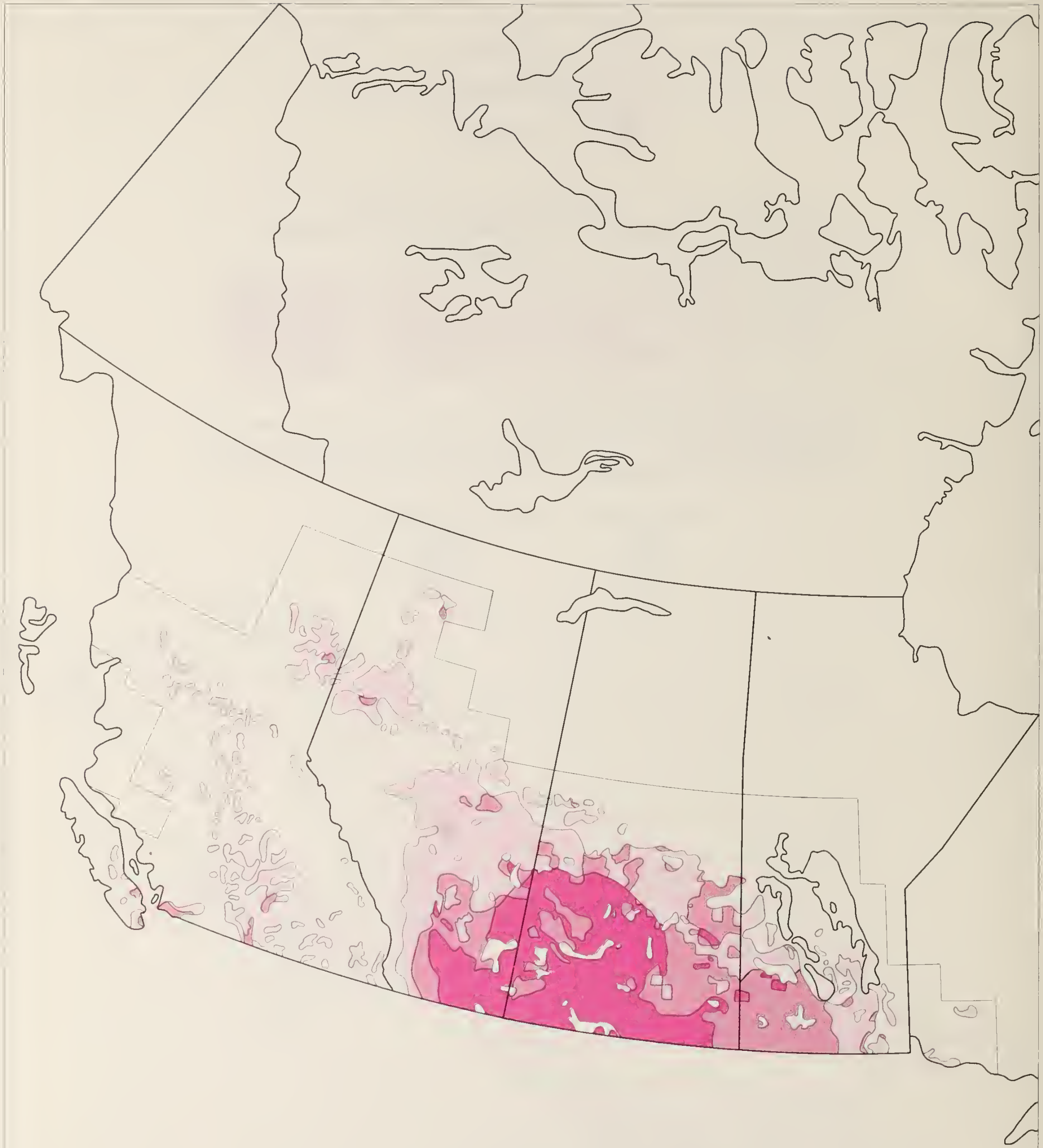
(1) Based on published and unpublished soil survey data.

(2) From: Atmospheric Environment Service, 1975. Canadian Normals, Vol. 3, Wind, 1955-72. Environment Canada, Downsview, Ont.

(3) From Chapman, L.J.; Brown, D.M. 1966. The Climates of Canada for Agriculture, Soil Moisture Classes. Canada Land Inventory, Report #3, Ottawa:

Moisture Class	Range in Water deficit (mm.)
LM	0–75
HK	75–125
EFG	125–230
CD	>230

Map 4



Map 5: Relative Wind Erosion Risk Modified by 1976 Cropping Practices

Cartography compilation and drafting by the Land Resource Research Institute, Research Branch, Agriculture Canada, 1981.

Low; see table below

Moderate; see table below

High; see table below

Relative Wind Erosion Risk(1)	Cultivated Land (% of improved land)(2)	Summerfallow (% of cultivated land)(3) <30	30–40	>40
Low	<30			
	30–75			
	>75			
Moderate	<30			
	30–75			
	>75			
High	<30			
	30–75			
	>75			

(1) From Map 4.

(2) Cultivated land = land under crops − total tame hay + summerfallow; Statistics Canada, 1976 Census of Agriculture.

(3) Summerfallow is defined in Statistics Canada, 1976 Census of Agriculture and is expressed as percent of cultivated land.

Map 5

Conserving crop residues is the most effective way of reducing wind erosion, especially in those areas most affected by the freezing, thawing and drying cycles generated by chinook winds (56). The current interest in zero tillage for prairie field crops suggests that, when mechanical and pest control problems associated with zero tillage are reduced, it may become a more widely accepted practice with a corresponding decline of wind erosion. Also there is a trend to reduced use of summerfallow in Alberta and Manitoba, with consequent better control of wind erosion. In Saskatchewan, however, ratios of summerfallow to cropland are as high as ever (24, 25).

In the more humid areas of these provinces, wind erosion is of less concern due to the slightly higher precipitation, lower wind speeds, more extensive continuous and forage cropping, and more varied and more wind-retardant vegetation (trees and shrubs). However, excessive cultivation of Black Chernozemic soils will leave these soils light and fluffy and subject to local wind erosion. The Peace River district has occasional wind erosion problems under conditions of high wind and dry soils (119). However, they are less severe than in the south central prairies. In the sandy soils of the Souris River basin and of the upper and lower Assiniboine delta of Manitoba, wind erosion has been quite severe in the past and appears to be a continuing problem (54). Scattered areas throughout the Red River valley have also suffered from wind erosion to the point that B horizon material is now brought up in tillage operations (53).

Drifting is also a hazard in the organic soil area of Manitoba. Efforts to drain and cultivate these soils for grain crops, with little modification of tillage practices from those used with mineral soils, has increased the wind erosion risk with these soils.

3.3 The Great Lakes - St. Lawrence Region

Wind erosion is a growing problem in southwestern Ontario (6). The main risk period is in late winter, spring and early summer when wind or snowmelt exposes plow-furrow ridges after frost action has desiccated and crumbled the soil clods. High winds at this time cause considerable soil drifting. During and after cultivation, especially in unusually dry springs, soil blowing can also be a problem. It occurs particularly where fences and hedgerows have been removed; where excessive cultivation has been practiced for some time; or where soils are low in organic matter, and structure and aggregation are weak.

In the sandy soils of Norfolk County in Ontario, and along the north shore of Lake Ontario, there was considerable drifting in the early days of clearing and cultivation. Some sand dunes have been stabilized by tree plantations and in areas where sand dunes did not form, windbreaks have been planted to permit cultivation, generally for tobacco. Poor management of these and other sandy soils renders them susceptible to blowing, particularly where they are used for corn or potatoes. Dufferin and Simcoe counties of Ontario are examples of such areas.

A potential problem is also developing in the soils of eastern Ontario and southern Quebec which are rapidly being converted from cereal-forage rotations to corn. The hazard is greatest where cultivation is accompanied by fence and hedgerow removal to obtain larger field units, and where continuous cultivation is practiced. Farther east, higher precipitation, less intensive cultivation and extensive forestry mitigate against a severe wind erosion problem at this time; however, there are large areas of shallow sandy soils in Quebec on both sides of the St. Lawrence River east of Montreal where wind erosion will accompany land clearing and cultivation.

Another wind erosion hazard area exists in the intensively cultivated organic soils located throughout the region. These soils blow away readily when dry and require windbreaks, water table management and strip cropping to prevent soil loss. Unfortunately, such practices are not widely used.

3.4 The Atlantic Region

Wind erosion in this region is less of a problem than elsewhere in Canada because of higher precipitation, greater use of forage crops and extensive areas of forest. Prince Edward Island appears to have the greatest potential for wind erosion because of the sandy soils, characteristic high winds and large percentages of the land area that are cultivated (Maps 4 and 5). Wind erosion is still considered to be a minor problem there, but no measurements of soil loss rates have been made.

4.0 SOIL ORGANIC MATTER LOSS AND COMPACTION DUE TO CULTIVATION

Tillage generally results in considerable changes in the quantity and quality of natural soil organic matter. In the first few years after a soil has been broken, the soil provides nutrients for crop production and the continuing high organic matter levels and microbial activity ensure a stable, well-aggregated soil structure. This structure maintains high infiltration rates of rainfall and snowmelt, good bearing capacity for tillage equipment and a well-aerated root zone. After a period of years, however, soil structure begins to deteriorate. This occurs as a result of declining organic matter content due to oxidation and microbial decomposition, and physical pulverization and compaction due to tillage. This situation may not become evident for many years, depending on the soil type, climate and quantity of organic matter that was present originally.

Organic matter and organic nitrogen in soils have been shown to exist according to a balance between input and loss (16, 69). These are determined by the crop grown, residue management, the type and frequency of cultivation, the fertilizer and manuring practices used, and the climate. Thus, for every set of crop rotation and management conditions, there will eventually be a characteristic organic matter content for the soil type and climatic conditions at any given site. This equilibrium level of organic matter, however, will almost always be below that which existed in the virgin soil.

Almost any decline in the organic matter content of mineral soils is of concern, chiefly because it is a major factor in soil structure and a loss of structure renders soils more susceptible to water and wind erosion and compaction. At the same time organic matter is a major source of soil nitrogen and micronutrients, and gives the soil improved cation exchange and water holding capacities. As such it is a resource of considerable importance for any agricultural production system.

The fate of all the nitrogen released from mineralization of organic matter is not always clear. Leaching and denitrification are both mechanisms of loss from the soil-plant system, but symbiotic and non-symbiotic fixation is a source of N addition. Some studies have indicated that organic N declines after cultivation more rapidly than organic carbon (34, 67), while others suggest the opposite (18). It is likely that the loss rates are actually very similar.

Soil compaction or structure deterioration often causes conditions where moisture infiltration or plant root extension is limited by high soil density and lack of macropore space.[1] This can result from mechanical disturbance through tillage, sometimes without a reduction in organic matter content as is the case with tillage of wet soils, or through excessive weight or speed of farm machinery. However, such conditions can also exist naturally in some soils and are not necessarily the result of soil degradation.

Map 6 identifies the regions of Canada most susceptible to soil organic matter loss and compaction resulting from cultivation. The map is based on the percentage of improved land that is cultivated, summerfallowed and row-cropped, the mean annual soil moisture deficit and the dominant soil texture class. Soil moisture deficit provides an indication of organic matter oxidation rates and the likelihood of tillage under wet conditions.

4.1 The Cordilleran Region

The relatively high rainfall, high water tables and intensive cultivation of row crops in the lower Fraser valley have led to some compaction and plow pan problems in medium and fine textured soils. The large, powerful rototillers that are quite common in this region produce a very fine seedbed but can cause considerable damage to soil structure. Fertilizer use is widespread, and consequently no major efforts are being made to maintain soil organic matter for reasons of nutrient supply.

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[1] The Western Canada Soil Coordinating Committee publications, Quality Criteria for Agriculture (127), indicates that the upper limit of bulk density in the Ap horizon should be 1.6 g/cm^3 .

In the interior valleys, such as the Okanagan, the semiarid climate has produced Chernozemic soils which have moderately high levels of natural organic matter and fairly strong soil structure. Problems are not generally encountered when these soils are used for intensive agriculture. Others, such as the Brunisolic soils, are low in organic matter and have weak surface structures. Such soils are generally under coniferous forest and are very common in many of the valleys and on some lower side slopes (120). Irrigation is commonly required when these dryland soils are cleared and cultivated. Observations suggest that proper tillage, irrigation and incorporation of crop residues over time have improved some of the poorer soils. While not a direct result of cultivation, soil compaction has been observed in irrigated orchards in the Okanagan Valley. Repeated traffic, including grass mowing, have compacted some silty soils so that irrigation water no longer infiltrates at a sufficient rate. Cultivation, in this case, seems to alleviate the problem.

4.2 The Great Plains Region

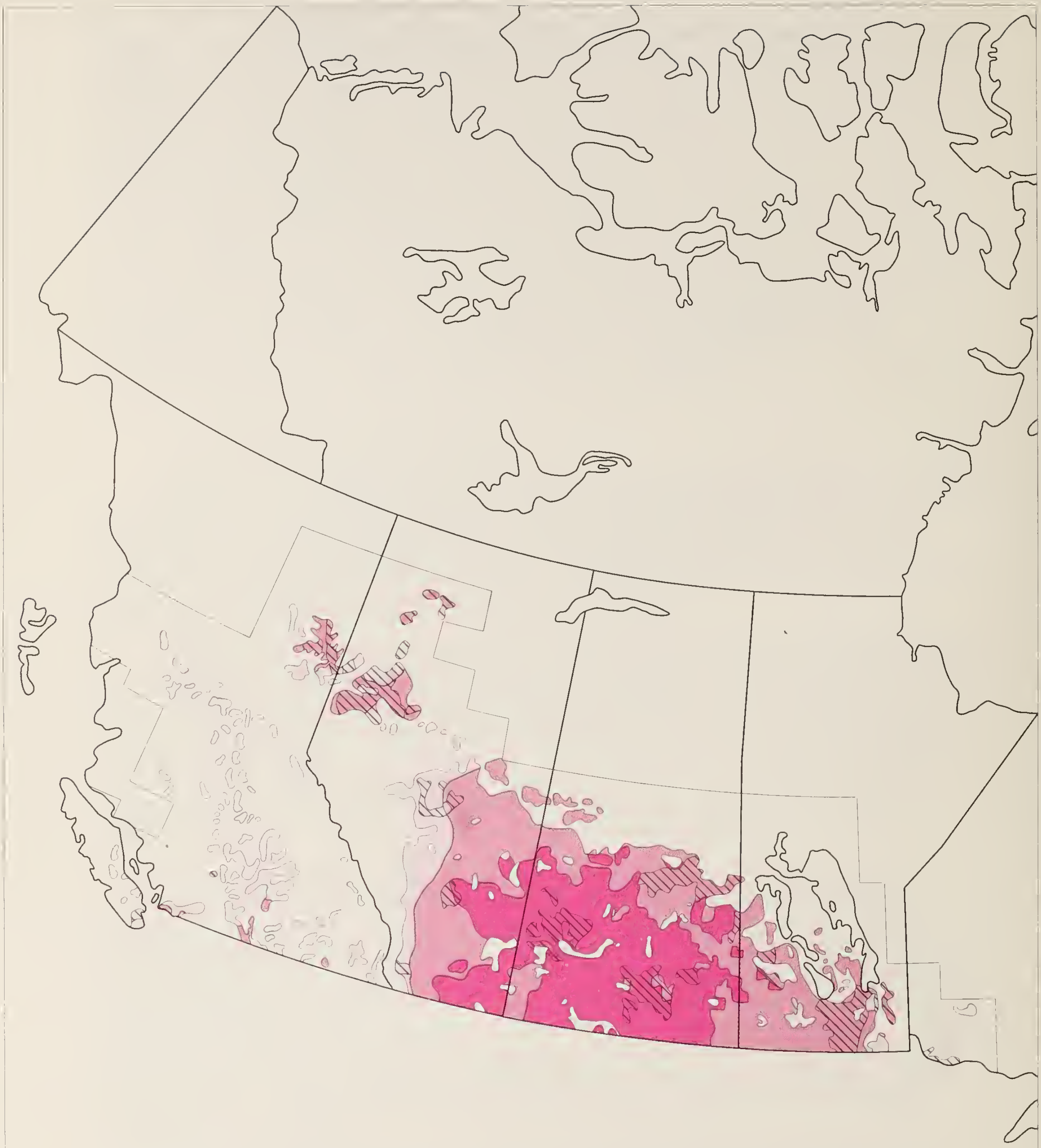
Native soil organic matter levels on the prairies tend to be high. The Black Chernozemic soils have natural organic matter levels which can be as high as 15%, but are more typically about 5-10%, while in the Dark Brown and Brown soils they may be expected to be 3-7%. This organic matter is mineralized after cultivation and releases nitrogen and other nutrients which can be used by crops.

Mineralization rates vary with soil types, cropping practices and the length of time under cultivation. Some research conducted over many years has shown that loss of organic carbon and nitrogen is most rapid in the first 5-6 years after cultivation, while other studies found little change in the rate of loss over time (19, 34, 77). Some work has shown that continuous cropping results in a lower rate of organic matter loss than summerfallow rotation, while other results indicate little difference between them (19, 90, 92).

The loss of soil organic matter is of concern in this region because of nutrient budgets as well as soil structure maintenance. Precipitation is low in the southern area and leaching of nitrate does not appear to be excessive, although some does occur particularly in the spring after snowmelt (19, 90). Denitrification also accounts for some loss of mineralized N. As organic matter levels decline under either summerfallow rotations or continuous cropping, increased fertilizer use is required to maintain crop yields. As long as organic matter levels do not decline to the point where soil structure begins to deteriorate, organic matter mineralization is a means of obtaining inexpensive nitrogen.

In the north central part of the region, where precipitation is higher, continuous cropping with small grains and oilseeds using fertilizers maintains a higher level of organic matter than that under summerfallow rotations. Crop rotations incorporating a forage legume, or the use of manure, can reduce or even prevent the net loss of organic matter from a cultivated soil (77, 92). Zero tillage may improve the situation by reducing soil disturbance and retaining more snow over winter, thus ensuring a better crop if conditions are dry. Use of a legume grain (such as lentils) in rotation with wheat and rapeseed has been suggested as a further improvement where climatic conditions permit (82).

Map 6: Relative Risk of Soil Organic Matter Loss and Compaction Estimated from 1976 Crop Distribution



Map 6: Relative Risk of Soil Organic Matter Loss and Compaction Estimated from 1976 Crop Distribution

Cartography compilation and drafting by the Land Resource Research Institute,
Research Branch, Agriculture Canada, 1981

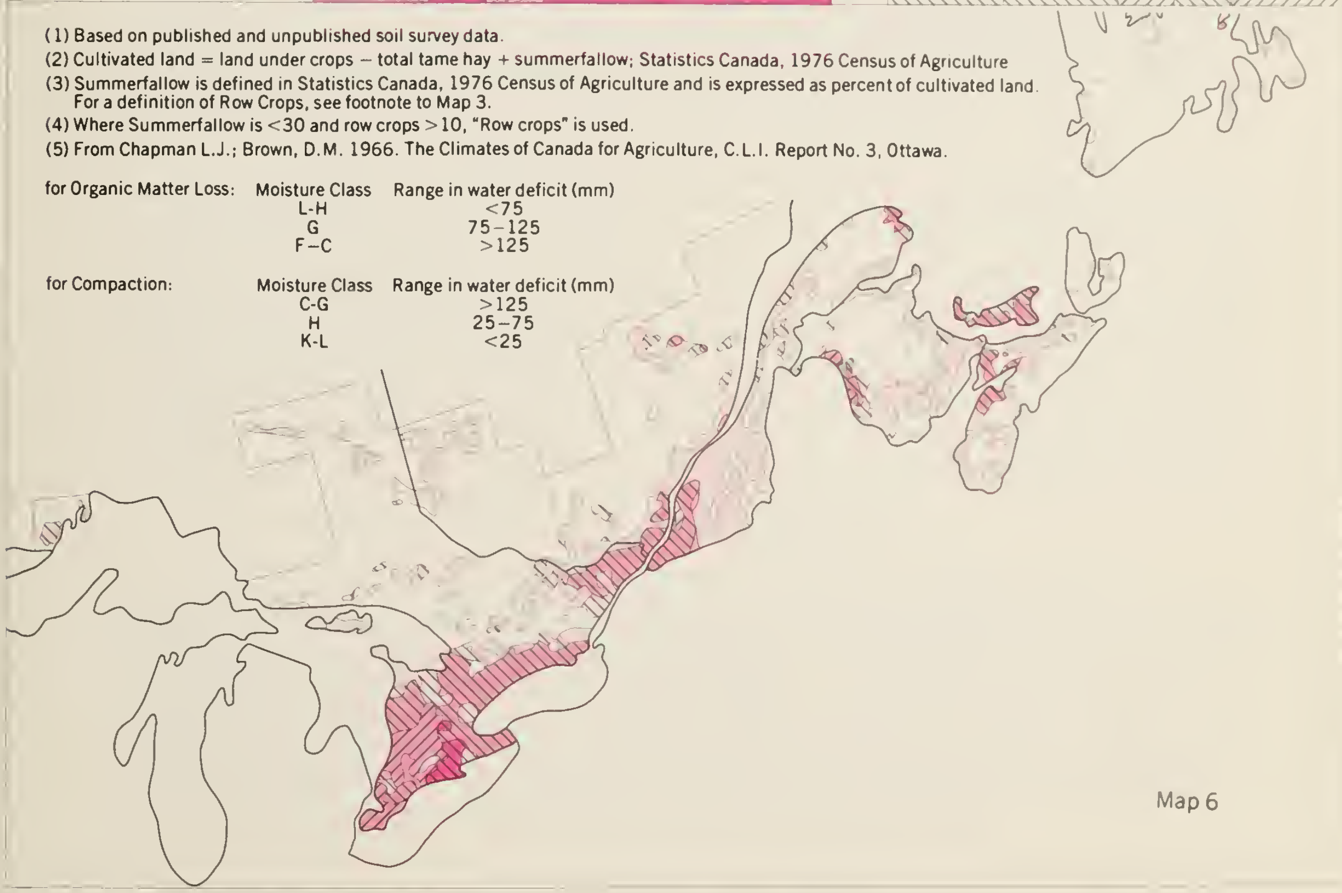
Organic Matter Loss		Compaction	
Low;	see table below	Low;	see table below
Moderate;	see table below	Moderate;	see table below
High;	see table below	High;	see table below

Surface Soil Texture[1]	Cultivated Land (% or improved land)[2]	for Organic Matter Loss									for Compaction								
		Summerfallow (S f) and/or Row Crops (R.C.)[3]									Row Crops[3]								
		Sf <30% and R.C. <10%			Sf 30–40% or R.C. 10–25% (Sf ≤40% and R.C. ≤25%)[4]			Sf >40% or R.C. >25%			<10%			10-25%			>25%		
		Soil Moisture Class[5]									Soil Moisture Class[5]								
		L-H	G	F-C	L-H	G	F-C	L-H	G	F-C	C-G	H	K-L	C-G	H	K-L	C-G	H	K-L
Clayey	<30																		
	30–75																		
	>75																		
Loamy	<30																		
	30–75																		
	>75																		
Sandy	<30																		
	30–75																		
	>75																		

(1) Based on published and unpublished soil survey data.
(2) Cultivated land = land under crops – total tame hay + summerfallow; Statistics Canada, 1976 Census of Agriculture
(3) Summerfallow is defined in Statistics Canada, 1976 Census of Agriculture and is expressed as percent of cultivated land. For a definition of Row Crops, see footnote to Map 3.
(4) Where Summerfallow is <30 and row crops >10, "Row crops" is used.
(5) From Chapman L.J.; Brown, D.M. 1966. The Climates of Canada for Agriculture, C.L.I. Report No. 3, Ottawa.

for Organic Matter Loss:	Moisture Class	Range in water deficit (mm)
	L-H	<75
	G	75–125
	F–C	>125

for Compaction:	Moisture Class	Range in water deficit (mm)
	C-G	>125
	H	25–75
	K-L	<25



Map 6

Wide-spaced row crops such as corn have been shown to lead to more organic matter loss than close-grown cereals because of inter-row cultivation (92). There has been a slow but general trend towards increasing use of row crops, such as corn for silage, in this region over the past 25 years (24, 25).

Overgrazing, burning and erosion, as well as cultivation, all have an impact on soil organic matter loss. Overgrazing of fescue range has been shown to change the soil microclimate to that of a drier soil; that is, an overgrazed Black soil can assume the colour, pH, moisture, temperature and organic matter content characteristic of a Dark Brown soil (55). It may also increase soil erosion. The situation, however, is not general since other studies have shown increases in soil organic matter under heavy grazing of other prairie grasses (103). Burning of straw and stubble is still practiced in some parts of the prairies, especially in Manitoba. Weed control has been one justification for stubble burning. The length of time that this practice can be continued before soil structure problems develop is not known.

Organic matter loss also results from intensive cropping of some irrigated soils. However, incorporation of crop residues such as corn stover and sugar beet tops, and the use of manure where available, can arrest and even reverse this decline (37).

Soil compaction problems are not extensive in the Prairie provinces. The low rainfall of the area, the intense freeze-thaw conditions during winter and the relatively high organic matter content of the soils reduce the risk of compaction, even where heavy tillage equipment is used. There is some concern among soil specialists, however, that compaction may eventually occur in clay soils of this region.

In a study of 5 years of excessive tillage (up to 12 tillage operations per year) on summerfallow on loamy Black Chernozemic soils with 12% organic matter in Alberta, no significant effect was found on bulk density at depths of 12-20 cm (33). Moisture content of the soil to the 90-cm depth was also unaffected. Dry aggregates <0.84 mm (the wind-erodible fraction) were not affected by tillage, except that there was an inconsistent seasonal effect and it was observed that plowing tended to increase the size of the aggregates. In a Manitoba study where various rates of organic matter were added to a Black sandy loam soil, no effect was observed on bulk density or dry aggregates (42).

4.3 The Great Lakes - St. Lawrence Region

Soil and crop specialists in the intensive farming zones of southern Ontario and southern Quebec are concerned about declining soil structure resulting from repeated tillage, but the effects of tillage in this area are still poorly documented. The region continues to experience marked changes in farm systems with monoculture corn, soybeans and other wide-row crops increasing steadily at the expense of crop rotations. In southwestern Ontario it is estimated that half the total farm area is in continuous row-cropping (59).

Fencerows are being removed in this region to enable the use of large machinery. This increases field sizes and slope lengths, resulting in increased wind and water erosion. The more powerful equipment has often resulted in more frequent and deeper tillage than is necessary and is used when soils are not sufficiently dry. Together with the decline in rotations, these trends have resulted in perceived, though seldom documented, deterioration in soil tilth, internal drainage and other physical properties. In some cases, yields have also been reduced, although the use of large quantities of fertilizer appears to have maintained productivity on most farms (59). Farmers have reported that tile drains in clay loam soil can practically cease flowing after a number of years of continuous corn, then resume flow after only a few years under alfalfa.

Table 5 shows some of the few available data on soil organic matter levels and tillage practices in this region. It is evident that the more frequent the cultivation, the lower the level of organic matter. Other data show that these levels can equilibrate at significantly higher values if manure or organic matter is added (109, 124). Concurrent with the loss of organic matter has been a reduction in soil aggregation as evidenced by size and strength analyses of water-stable aggregates. Reductions of 40-60% in water-stable aggregation indices have been reported under continuous corn compared with a 4-year corn, oats, hay, hay rotation on various soils in southern Ontario (58). Fifty years of continuous sod on one of these soils left water-stable aggregation 60% higher than that under rotation (13). Three cultivated soils in southern Quebec used for a grains and forage rotation had water-stable aggregation indices ranging from half to one-fifth the values in the same soils in the undisturbed state (67). Both water-stable and dry aggregates increased dramatically with time over a 25-year period of continuous sod on both a clay loam and a sandy loam soil in Quebec, while water-stable aggregation in the clay loam soil dropped an order of magnitude under continuous corn compared with that under a 5-year rotation (68).

Compaction problems in this region arise primarily from repeated tillage and working of the soil when wet. These problems are most often observed in fine textured soils, though greater increases in soil bulk density have been observed in some sandy soils when these have been subjected to tillage traffic (88). While declining soil organic matter levels contribute to the problem, poor soil drainage is another factor that increases the likelihood of tillage and harvesting operations being done on wet soils, which make mechanical compaction more severe.

Over 90% of the subsurface drainage work in Canada has been done in Ontario. Nevertheless, about twice the currently drained area in this province is still in need of improved drainage (22). Subsurface drainage installation rates have greatly increased in recent years in Quebec, accompanying the increased production of cash crops and silage corn.

Table 5. Organic matter levels in surface soils of the Great Lakes - St. Lawrence region as influenced by cropping practice

Soil type (series)	Percent organic matter (no. of years)				Ref. no.
	Undisturbed	Continuous sod	Rotation	Continuous corn	
Clay loam (Brookston)	-	8.1 (50)	4.9 (5)[1]	3.7 (5)[4]	13
Clay (Haldimand)	7.6	4.5 (8)	4.9 (8)[2]	4.0 (8)	124
Loam (Guelph)	6.5	4.4 (10)	4.1 (10)[2]	3.1 (10)	125
Clay loam (Kamouraska)	11.4	6.5 (25)	6.3 (30)[3]	-	67
Clay loam (Ste. Rosalie)	-	-	6.3 (>10)[3]	4.1 (8)	68
Sandy loam (Charlevoix)	7.3	-	6.3 (30)[3]	-	67

[1] Corn, corn, oats, hay, hay.

[2] Corn, oats, hay, hay.

[3] Cereal, hay, hay, hay, hay.

[4] Following 30 years of cultivation for other crops.

Little consistent experimental evidence is available to support the observation that larger tractors and machinery cause soil compaction. Studies on Brookston clay in southwestern Ontario between 1952 and 1955 found that there was a slight, but not significant, trend for excessive tillage traffic to reduce pore space at depths between 5 and 15 cm, but there was even less effect on yields (14). On the other hand, recent work indicates that continuous corn in southwestern Ontario has a detrimental effect on both total and air-filled soil pore space, causing compaction (15). The result of this compaction was found to be reduced crop uptake of nutrients, especially N and K, resulting in reduced yields. Fertilizer use was found to compensate for inefficient N use, but not for K. The study indicated a concern for the long-term viability of continuous corn on fine textured soils of Ontario, and demonstrated the value of forage legumes in a rotation with corn in terms of improved soil physical conditions and more efficient fertilizer use.

Studies of traffic compaction on a clay soil in southern Quebec showed increases in bulk density from traffic by a tractor smaller than that used in the earlier Ontario study (87). The greatest effect was observed in the first five passes, with increases in bulk density of up to 0.25 g/cm^3. Similar results were obtained in a sandy loam orchard soil. Bulk densities under a section of orchard established on this soil for 34-40 years were approximately the same as those after 15 passes with the tractor. It was concluded that roots, freezing and thawing, wetting and drying, and so forth, over a period of years must have moderated the effect of repeated vehicle traffic, as many more than 15 passes with tractors would have occurred over the life of the orchard.

Excessive tillage at a constant depth encourages the formation of a "hardpan" (or plow pan) which restricts root penetration, and moisture and nutrient availability. Quebec studies have confirmed that the maximum effect of tractor weight occurs at depths between 12 and 26 cm (88). In spite of the intensity of cultivation of these Great Lakes and St. Lawrence soils, few examples of plow pans have been reported in the literature. Unpublished data from a study now being conducted by the senior author, however, confirm the existence of the problem in several eastern Ontario soils.

The overall degree of soil compaction and structure deterioration now occurring as a result of continuous cropping and tillage in the agricultural soils of Ontario and Quebec is far from clear. However, some observers have rated it as the most serious soil degradation problem of this region.

4.4 The Atlantic Region

The Atlantic region has cropping and cultivation trends similar to those of the Great Lakes - St. Lawrence region, with the principal row crops being corn and potatoes. Many soils have naturally compact subsoils and weak surface structure, and a surplus of moisture is a common problem which often leads to tillage under wet conditions. In potato growing areas, soil erosion has already removed surface soil to considerable depths (111, 112), and organic matter levels in the remaining material are often low. In similar soils in the State of Maine, studies have shown that while continuous potatoes did not significantly decrease organic matter levels compared with rotation cropping, water-stable aggregation was decreased, and soil loss and runoff were increased (99).

Severe erosion and stone removal has brought subsoils closer to the surface of some soils, causing inherent compaction to be more detrimental to crop production than it would be in recently cleared land. The effects of intensive cultivation for potatoes is compounded by the considerable weight and vibration common to the harvesting machinery. Furthermore, these machines are often used when soils are wetter than desirable for maximum resistance to compaction. Some New Brunswick soils have been found to increase in bulk density by over 17% in 1 year of potato cultivation and harvesting (100). Twelve passes with a tractor in an experimental setting caused the same degree of increase in bulk density, while crop yields were reduced by 21%. Similar problems were observed with corn production, and frost action did not appear to relieve the compaction problems significantly in these soils (98). Data have been published which show a steady increase in soil bulk density with the number of years of potato growing (99). However, this concept of accumulating compaction is not accepted generally across Canada, and clearly needs more research.

Prince Edward Island soils are relatively low in organic matter content, with most soils falling in the range of 2-4% (96). Such levels are approaching the critical organic matter thresholds below which soil aggregate stability declines rapidly (123), indicating that a relatively small deterioration in soil organic matter brought about by intensive cultivation could have a serious impact on soil structure. According to provincial soil testing service data for the past 5 years, such decreases are occurring (112, 123).

While data are scarce, it is evident that the increasing production of corn in the Atlantic region, coupled with the continuous cultivation of potatoes on soils long used for this purpose, presents a prospect of potentially severe soil degradation. The region has a high annual rainfall, much of which occurs in the fall when soils are bare and unprotected, and it has the wettest soil moisture classes in the country. Observable erosion is often severe, yet the potential impact of present cropping and tillage trends is not well recognized.

5.0 SOIL SALINIZATION

Soil salinization results from an increase or redistribution of soil salts which occurs by processes involving the evaporation of water and salt precipitation in or on the soil. Alkalinization is sometimes associated with salinization and occurs through increases in sodium salts. This increases soil exchangeable Na and soil pH. The sodium percentage generally approximates that of the local groundwater. When conductivities of saturated water extracts of the surface soil exceed 4 mmhos/cm, a soil is considered saline. At this level of salinity many crops will still grow, but at 14 mmhos/cm, only very tolerant native weeds can survive.[1] When more than 15% of the exchangeable bases of any of these saline soils is sodium they are known as saline-sodic or saline-alkali soils, and may have a very poor physical condition, depending on the amount of Na present (46).[2]

High levels of salinity reduce germination and growth of most crops by interfering with water and nutrient transport mechanisms across the soil-root interface. The salts are usually sulfates, chlorides, carbonates and bicarbonates of calcium, sodium and magnesium. A high sodium percentage also causes the formation of dense subsurface soil horizons which reduce hydraulic conductivity. High pH levels interfere with nutrient uptake and reduce crop growth. While there is a wide range of salinity tolerance among varieties of any particular crop, there is a general tendency for tolerance to be greatest in forages and to be lower in cereals and oilseeds with vegetables the most sensitive.

Soil salinization is caused by transport of salt in soil solutions, followed by evaporation and precipitation in or on the soil. The balance of water movement between the soil and shallow groundwater can be altered by cultivation and by removal of perennial native vegetation, which is capable of greater transpiration than many agricultural crops so that the situation is worse under summerfallow, when no crop is grown. The net result is downslope migration of percolation water over slowly permeable till or bedrock, with enrichment in salt content from inherent subsoil salinity. When this moisture enters a discharge zone, often at the base of a slope, in a depressional area, or at a change in slope or soil type, evaporation and capillary action cause the salts to be deposited at the soil surface and in the profile, and a saline-seep condition develops (7, 46, 106, 121).

Salinity in irrigated areas commonly occurs when water tables are raised in the vicinity of canals because of leakage, or as a result of seepage and excessive water applications. As irrigation water raises water table levels or moves through the subsoil, it brings dissolved salts nearer the surface. When this water evaporates, the salt content of the remaining soil water increases until crop damage results and salt-tolerant weeds invade the area. Further evaporation results in the destruction of all vegetation, and eventually the formation of salt crusts.

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[1] The Western Canada Soil Coordinating Committee publication, Soil Quality Criteria for Agriculture (127), indicates limitations to crop growth when conductivity of saturated paste exceeds 2 mmhos/cm, and severe limitations at 12 mmhos/cm.

[2] The large areas of Solonetzic soils in the western prairies are not considered to have a soil degradation problem in the context of this assessment.

Map 7 presents an overview of soil salinization in western Canada. Soil salinization is essentially a problem of the Great Plains region. Alkalinization has not been shown separately as it is rare, and not readily identified or predicted. The map depicts six types of land:

i) Areas of saline soils which predate agricultural settlement.

ii) Solonetzic soils (excluding Solods) in which subsurface salinity, high in sodium content, is a permanent feature requiring special management.

iii) Areas in which soil salinization is active and there is a high risk of further salinization of agricultural land.

iv) Areas in which soil salinity may be found, but there is only a moderate risk of further salinization of agricultural land.

v) Land on which salinization is unlikely to occur and is rarely encountered. This includes areas in which precipitation and leaching are adequate to keep salts below the root zone, and areas where soil materials and topography generally preclude salinization of agricultural land.

vi) Irrigated land, assumed to have a variable potential for local soil salinization dependent primarily on irrigation and drainage management.

The classification of land within these categories has been based on published and unpublished maps interpreted through the experience of soil specialists.[1]

5.1 The Cordilleran Region

While small scattered areas of saline soils can be found in depressions in the dry interior plateau of this region, no widespread salinization or alkalinization problems have been noted. Salinity in irrigated areas is not common, but irrigation is practiced in a large number of small scattered areas on glacial lacustrine and fluvial terrace soils, and there are occasional saline seeps at associated downslope sites. In most cases, however, the land involved is not agricultural and the significance of the problem is minor.

In the Fraser valley delta some examples exist of marine salt water damaging dyked soils. These appear to be the result of faulty drain construction or the presence of sand lenses in the subsoil which allow salt water encroachment, but these problems are minor. Airborne salt from ocean sources is sometimes of concern in coastal farmlands but has not yet been noted as a problem in this region.

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[1] The assistance of Dr. A.K. Ballantyne, Saskatchewan Institute of Pedology, with the identification of soil susceptibilities to salinization is gratefully acknowledged.

5.2 The Great Plains Region

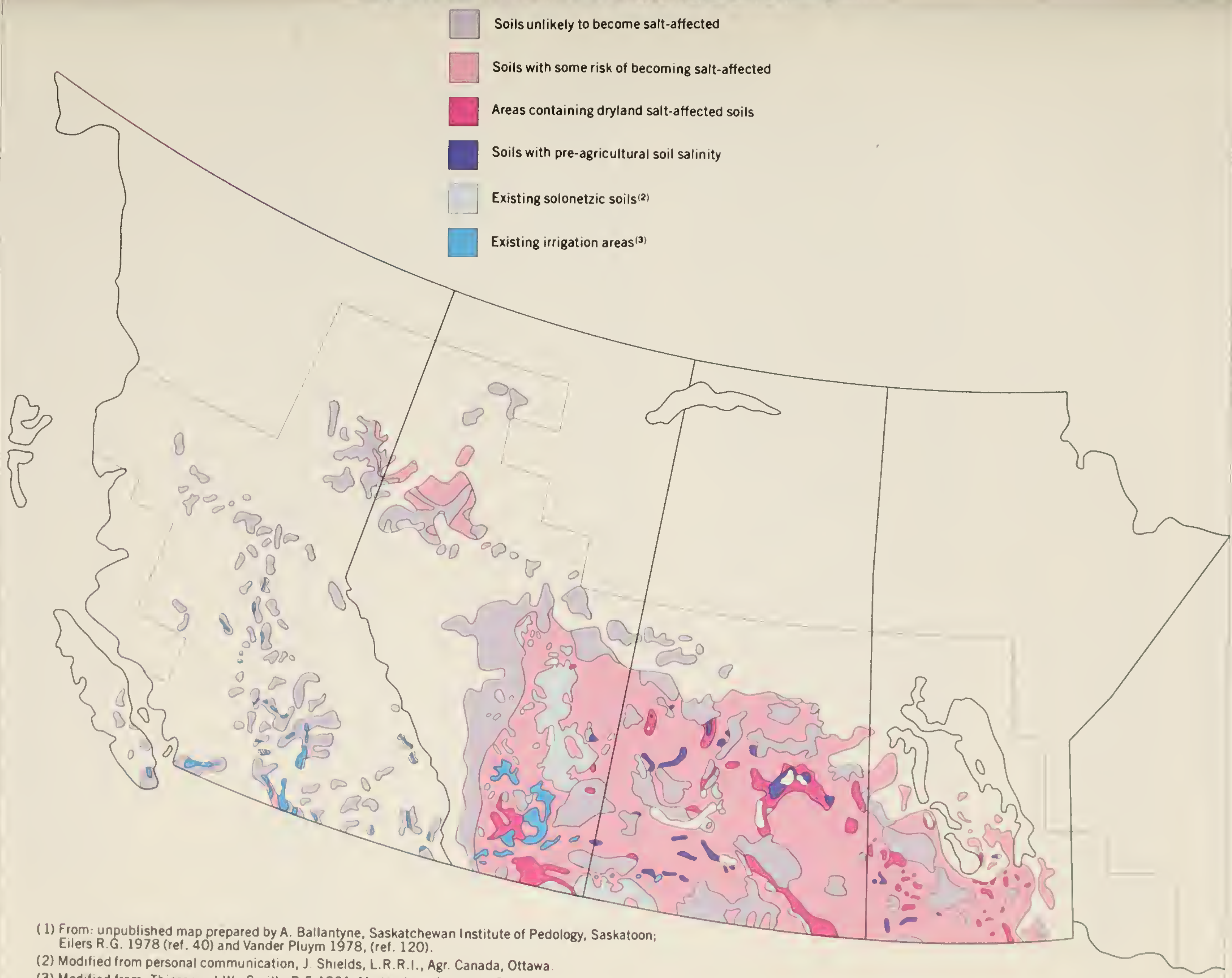
Soil salinization in the Great Plains region of Canada has been described as a developing problem of major proportions (121). It is believed that the effects of 80 years of depletion of native vegetation and cultivation are now showing up over a steadily widening area. The first reported scientific evidence of the process of saline-seep development in Canada was apparently as recent as 1962 (65). It is widely believed that the problem may become more serious in future wet years, even if measures are taken to revegetate areas in upland recharge zones in order to increase evapotranspiration and decrease percolation of rain and snowmelt (106). In any given year, however, salinization may appear to increase at some sites and decrease or remain unchanged at others. Such variability results from local differences in climate, water table levels and cropping practices (9).

Dryland salinity appears to have increased threefold over 10 years in cultivated land and twofold in rangeland in some parts of Alberta (121), and fourfold over 15 years in Saskatchewan (90). Such estimates are not available for Manitoba but there are areas of potential expansion by seepage which occurs at the base of the escarpment and in the Souris basin at the base of Turtle Mountain (39, 75). The problem appears to be increasing partly because of the widespread continuation of summerfallow even in years when it is not necessary for soil moisture requirements. Since the practice became widely accepted in the 1930's when annual precipitation in much of the prairies was below average, it has continued, sometimes as a weed control measure, even though moisture conditions have improved. The percolation of surplus moisture which accelerates salinization also causes the leaching of mineralized nitrogen from summerfallowed fields, and together these processes underscore the long-term undesirability of summerfallow practices.

Man-made alterations to the natural flow of water can also lead to saline seep development. Roads and railways, villages with septic tanks for waste disposal and shelterbelts where snow accumulates often result in a local increase in downslope water table levels, resulting in seep conditions.

Preventing a saline seep condition, or alleviating one once it has developed, is complex. The source area of seepage water is quite likely to be on the property of another landowner and can be at a considerable distance from the seep. Continuous cropping, seeding with forage crops and draining depressional areas where runoff collects may be needed in the recharge area. Yet these practices may be uneconomic or otherwise inconvenient for the landowner, particularly in the irregular topography typical of much of the region. Control at or near the seep includes lowering the water table by seeding deep-rooted, salt tolerant forage such as alfalfa if salinity is not severe. Such crops may also be used to intercept seepage by planting across the slope immediately above the seep area (20, 46). Continuous cropping using salt tolerant crops such as barley may also be possible in the seep area. Subsurface drainage by either tile or mole drains may be used to remove water and lower the water table (20, 108). However, the construction of suitable outlets for such drainage systems is a major expense constraining the feasibility

Map 7: Salt Affected Soils and Relative Risk of Soil Salinization[1]



(1) From: unpublished map prepared by A. Ballantyne, Saskatchewan Institute of Pedology, Saskatoon; Eilers R.G. 1978 (ref. 40) and Vander Pluym 1978, (ref. 120).

(2) Modified from personal communication, J. Shields, L.R.R.I., Agr. Canada, Ottawa.

(3) Modified from: Thiessen, J.W.; Smith, R.F. 1981. Modernizing Irrigation Systems in Alberta, Canada. Prepared for the 11th Congress on Irrigation and Drainage Grenoble, France, 1981; from; Influence of Man, Fisheries and Environment Canada, Hydrologic Atlas of Canada, Ottawa, 1978; and personal communication, A.B. Dawson, B.C. Ministry of Agriculture.

Cartography compilation and drafting by the Land Resource Research Institute.
Research Branch, Agriculture Canada. *1981*

of this practice. In one study in Alberta where no outlet was available, a dugout reservoir was constructed at the bottom of the depression for drainage water. This water was then successfully irrigated back onto the catchment watershed (83). The practice appears feasible where the salinity of the drainage water is not excessively high.

The vast majority of irrigated land is in Alberta, and of this about 45000 to 50000 ha, or 15%, is affected by some form of salinity (personal communication, Mr. Oosterveld, Agriculture Canada, Lethbridge). The majority of the affected areas are located downslope of poorly constructed canals that seep excessively. A program of relocating and lining canals with concrete, asphalt emulsion and rubber or plastic membranes is under way to reduce the seepage.

A recent Alberta planning report on irrigated land (Stanley Associates Consultants, Lethbridge, Alta. 1978) suggested widespread use of tile drainage to overcome existing salinity and waterlogging problems. There is general agreement that drainage is effective in reclaiming land that is now deteriorated, but there is less agreement on further expansion of waterlogging and salinity if drainage is not installed. More than half of water requirements in the area are met through natural precipitation and thus, with the use of a minimal amount of good-quality irrigation water, only a small amount of leaching would be needed to keep the soil salts in balance. In many areas the natural drainage rate is adequate to meet this leaching requirement (107).

Wind is also a mechanism for salt movement. It has been shown to cause soil salinization and alkalinization downwind of a dry saline-alkali lake bed in Saskatchewan (8). Another problem with wind-blown salt has been identified in soils downwind of a fertilizer potash plant (21). The extent of such occurrences is not known.

Some salinity problems have also been noted as a result of brine disposal from oil wells in Alberta and Saskatchewan. The area involved is very small, and current practice is to return this salt water to disposal wells.

5.3 Great Lakes - St. Lawrence and Atlantic Regions

No salinization or alkalinization problems have been identified east of Manitoba, due to the adequate precipitation and usual absence of salts in subsoils. Some problems exist with removal of salts from reclaimed coastal floodplain soils in the Bay of Fundy area, but these are beyond the scope of this report.

6.0 SOIL ACIDIFICATION

Acidification is the process by which bases are removed from the soil exchange complex and are replaced with hydrogen and aluminum, lowering the pH in the soil solution. Acidification is a natural and continual soil process, but the acidification under consideration in the context of soil degradation is that which is accelerated by man's activities.

Accelerated acidification is brought about by three principal processes:

i) Addition of sulfur, in the elemental form or as sulfides or sulfur dioxide, which oxidizes to sulfate, giving an acid reaction. This can occur through atmospheric emmissions from fossil fuel combustion and sulfur removal from natural gas plants, or from the use of sulfur-containing fertilizers. Sulfur is one of the principal acidifying agents in "acid rain."

ii) Applying nitrogen fertilizer, either as urea or in the form of ammonia or ammonium. Nitrification to NO_3^- results in release of H^+ and exchange with exchangeable bases. This problem is most acute in humid environments, and under irrigation where there is excess water for leaching. Atmospheric nitrogen also contributes to the acidification process.

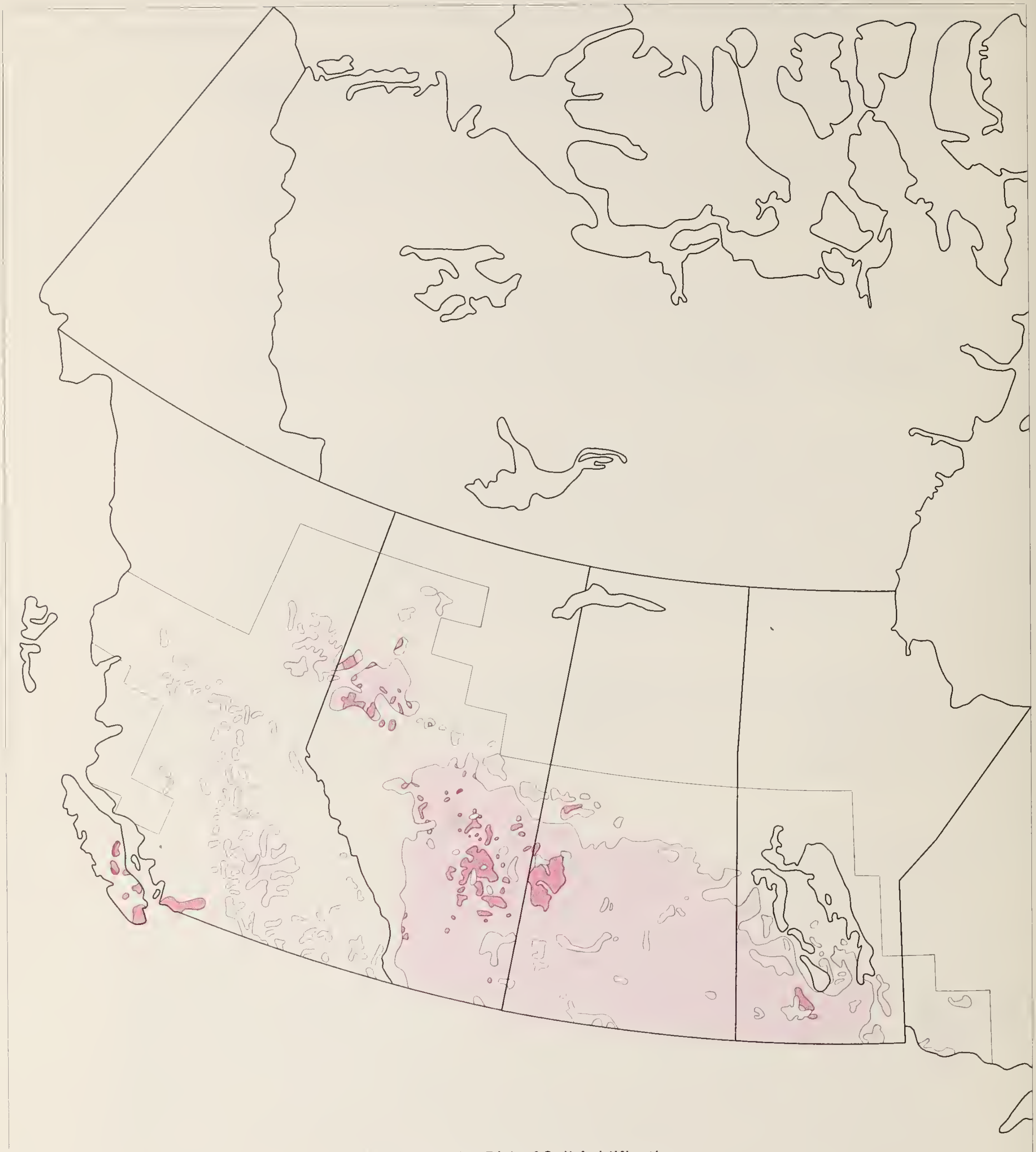
iii) Oxidation of sulfides to sulfates when marine sediments are drained. Sulfur compounds, especially pyrites, deposited with organic matter in ancient marine sediments, were reduced to produce sulfides by anaerobic bacteria. When these soils are drained they become aerobic and the sulfides are oxidized to sulfates, acidifying the soil. This is generally a local problem common only in dyked coastal floodplains and estuaries, but the process has been identified in other soils.

Accelerated acidification is of concern because it brings about a decrease in the availability of macronutrients and may increase the solubility of some micro-elements to toxic levels. In either case, crop growth is reduced and lime additions may be necessary, or where currently used they may be needed more frequently to maintain an optimal soil pH and base saturation.

Map 8 shows the relative risk of soil acidification based upon the present pH, degree of calcareousness and texture of surface soils, and the acidity derived from atmospheric deposition. Noncalcareous soils and slightly calcareous sandy soils may have few exchangeable bases to buffer against pH changes. Soils with pH values already below 6.0 have been included as they will become less suitable for some crops after only minimal decreases in pH. Soils in eastern Canada receive sufficient acidity from atmospheric deposition that their susceptibility to acidification from agricultural practices has been considered separately. There may be small areas in Alberta with atmospheric sulfur deposition high enough to affect soil susceptibility to acidification, but insufficient data exist to permit the delineation of any such areas on the map. Map 9 has been prepared to show the distribution of the present likelihood of soil acidification based on the use of nitrogen fertilizers and lime.

Map 8: Relative Risk of Soil Acidification

Map 9: Relative Soil Acidification Risk, Modified by Extent of Cultivated Land, Nitrogen Fertilizer Use and Liming



Map 8: Relative Risk of Soil Acidification

Cartography compilation and drafting by the Land Resource Research Institute, Research Branch, Agriculture Canada, *1981*.

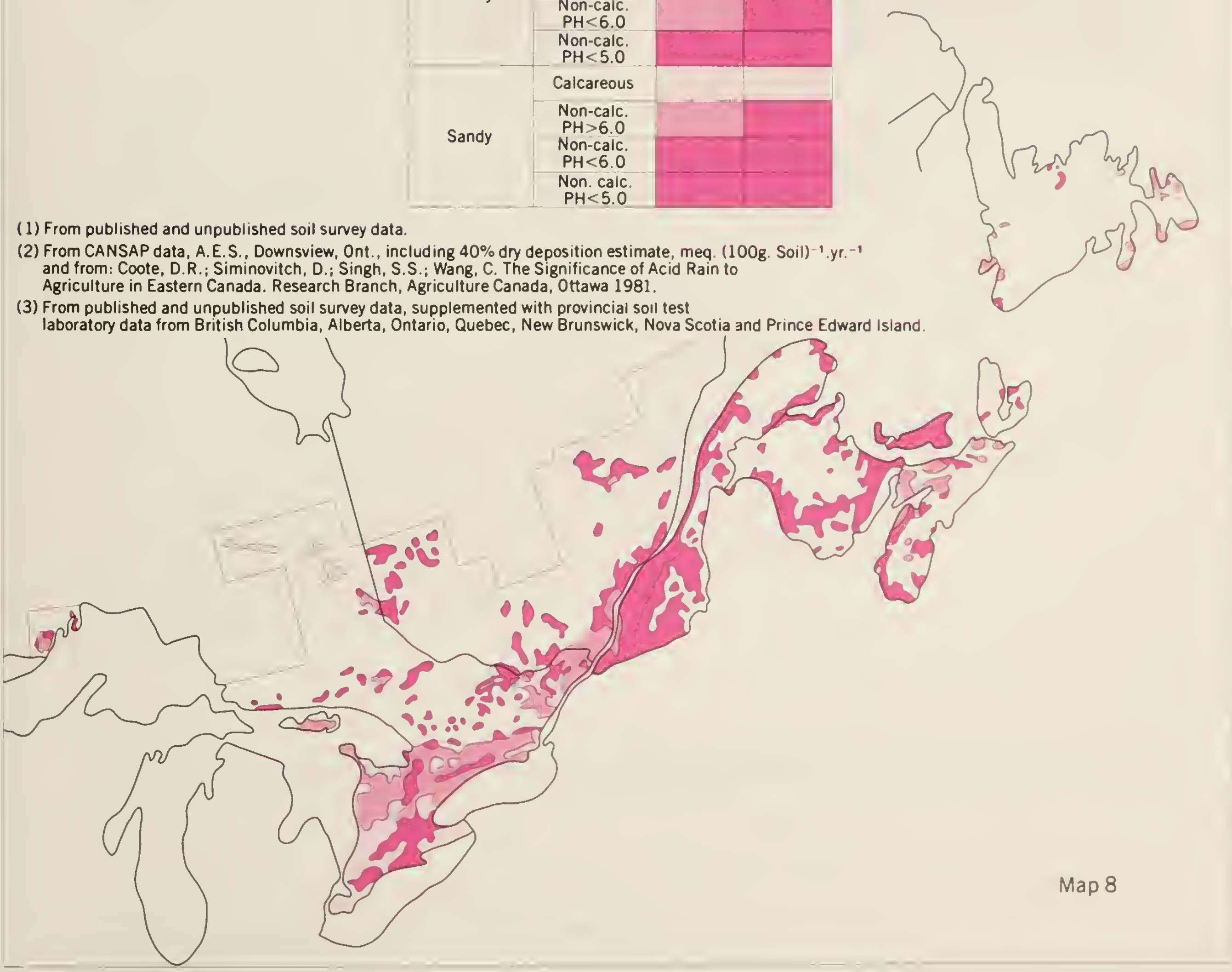
- Low; see table below
- Moderate; see table below
- High; see table below

Surface Soil[1]		Annual Atmospheric Deposition[2]	
Surface Soil Texture	Calcareousness and pH[3]	<20 meq. of acidity per 100g Soil	>20 meq. of acidity per 100g Soil
Clayey	Calcareous	Low	Low
	Non-calc. PH>6.0	Low	Low
	Non-calc. PH<6.0	Moderate	Moderate
	Non-calc. PH<5.0	Moderate	High
Loamy	Calcareous	Low	Low
	Non-calc. PH>6.0	Low	Moderate
	Non-calc. PH<6.0	Moderate	High
	Non-calc. PH<5.0	High	High
Sandy	Calcareous	Low	Low
	Non-calc. PH>6.0	Moderate	High
	Non-calc. PH<6.0	High	High
	Non. calc. PH<5.0	High	High

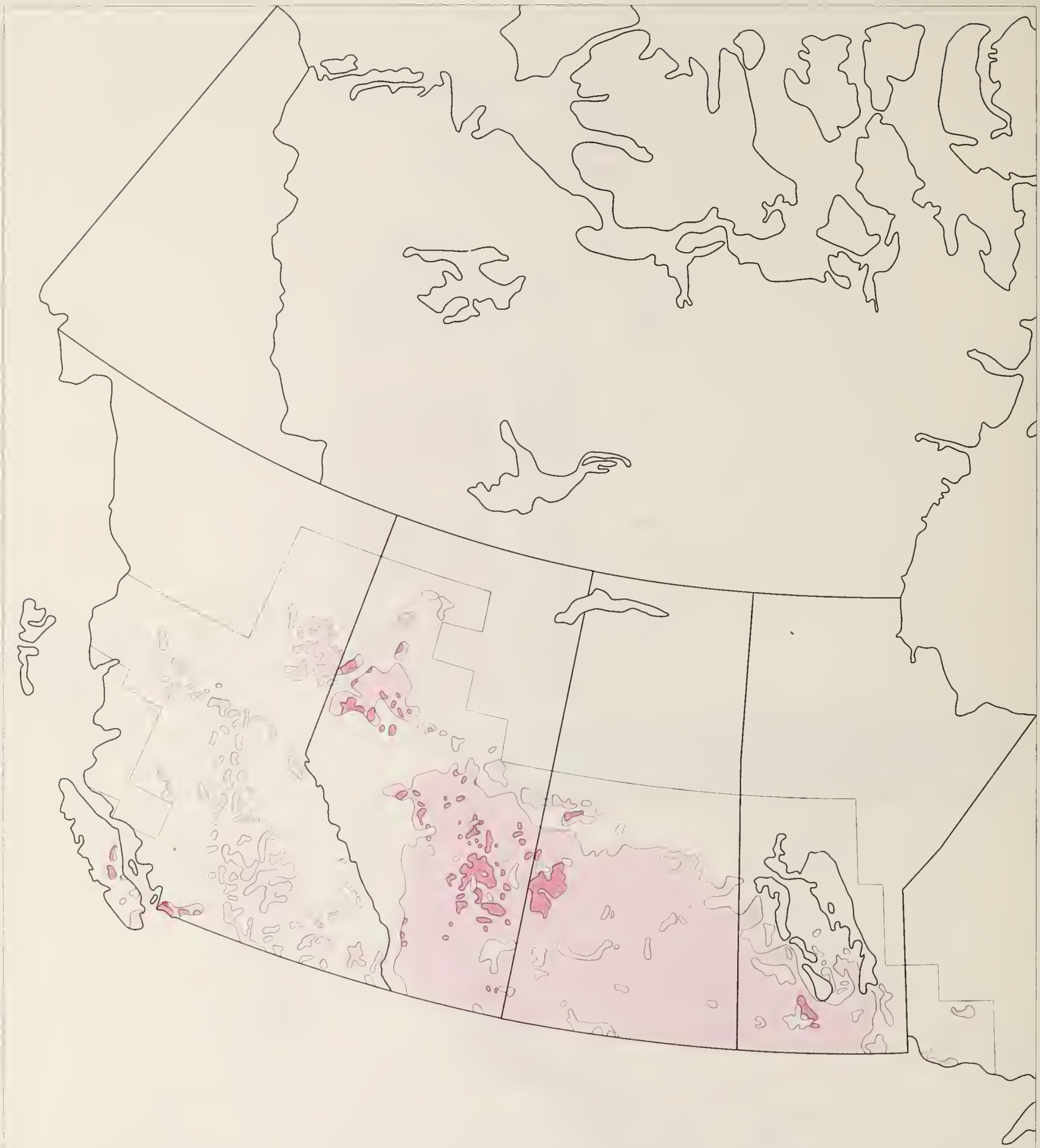
(1) From published and unpublished soil survey data.

(2) From CANSAP data, A.E.S., Downsview, Ont., including 40% dry deposition estimate, meq. $(100g.\ Soil)^{-1}.yr.^{-1}$ and from: Coote, D.R.; Siminovitch, D.; Singh, S.S.; Wang, C. The Significance of Acid Rain to Agriculture in Eastern Canada. Research Branch, Agriculture Canada, Ottawa 1981.

(3) From published and unpublished soil survey data, supplemented with provincial soil test laboratory data from British Columbia, Alberta, Ontario, Quebec, New Brunswick, Nova Scotia and Prince Edward Island.



Map 8



Map 9: Relative Soil Acidification Risk, Modified by Extent of Cultivated Land, Nitrogen Fertilizer Use and Liming

Cartography compilation and drafting by the Land Resource Research Institute,
Research Branch, Agriculture Canada, 1981.

Low; see table below

Moderate; see table below

High; see table below

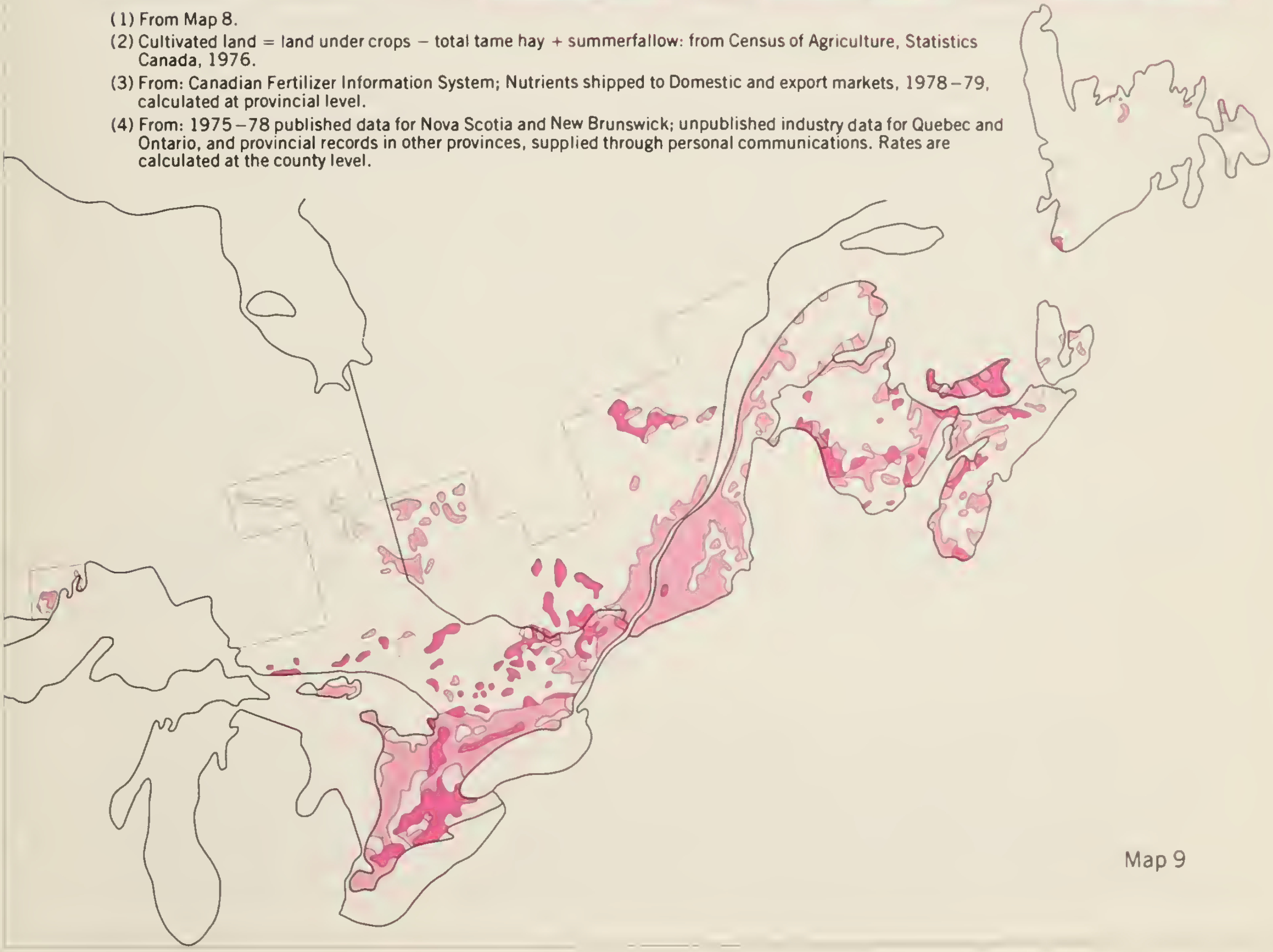
Risk of Acidification (1)	Cultivated Land (% of improved land)(2)	Fertilizer "N" Use (Kg/cultivated ha/yr)(3) 0-15			15-40			>40		
		Liming Rate (Kg/cultivated ha/yr.)(4) >1000	100–1000	<100	>1000	100–1000	<100	>1000	100–1000	<100
Low	<30	Low	Low	Low	Low	Low	Low	Low	Low	Low
	30–75	Low	Low	Low	Low	Low	Low	Low	Low	Moderate
	>75	Low	Low	Low	Low	Low	Low	Low	Low	Moderate
Moderate	<30	Low	Low	Moderate	Low	Moderate	Moderate	Moderate	Moderate	Moderate
	30–75	Low	Low	Moderate	Low	Moderate	Moderate	Low	Moderate	High
	>75	Low	Low	Moderate	Low	Moderate	Moderate	Low	High	High
High	<30	Moderate	Moderate	High	Moderate	High	High	High	High	High
	30–75	Low	Moderate	Moderate	Low	Moderate	High	Moderate	High	High
	>75	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High

(1) From Map 8.

(2) Cultivated land = land under crops − total tame hay + summerfallow: from Census of Agriculture, Statistics Canada, 1976.

(3) From: Canadian Fertilizer Information System; Nutrients shipped to Domestic and export markets, 1978–79, calculated at provincial level.

(4) From: 1975–78 published data for Nova Scotia and New Brunswick; unpublished industry data for Quebec and Ontario, and provincial records in other provinces, supplied through personal communications. Rates are calculated at the county level.



Map 9

Soils lose basic cations by leaching and crop removal at widely varying rates depending on climate, crop and the nature of the soil. These losses may range from an annual rate (expressed as $CaCO_3$ equivalent) of less than 50 kg/ha in a continuous cereal crop in a semiarid area with essentially no leaching, to more than 1000 kg/ha in a freshly limed sandy soil in a humid region (94). Average annual rates ($CaCO_3$ equivalent) are about 500 kg/ha. Thus, the additional lime requirement resulting from atmospheric inputs averages about 3% of this mean requirement (Table 6). The impact of nitrogen fertilizers is about four times this amount. Liming recommendations are usually based on soil data which include atmospheric and fertilizer effects, and thus the overall liming requirement is likely to recur more frequently where these impacts are highest.

6.1 The Cordilleran Region

Fertilizer and atmospheric inputs are moderate on noncalcareous soils of Vancouver Island and the lower Fraser valley, but soil test data show a decline in average soil pH between 1967 and 1975. In 1967, 65% of samples from Vancouver Island and 68% of samples from the lower mainland were at pH 6.0 or less, compared with 89% and 87% in 1975, respectively (50). Lime use in this area is substantial, being between 270 and 365 kg/ha annually (personal communication, P.B. Hoyt, Agriculture Canada, Summerland, B.C.). However, since a lime incentive program was discontinued in British Columbia in 1972, lime use has fallen by 10-20%.

In the interior of the region, most soils are developed on moderately calcareous parent materials. However, while only 8% of the soil samples sent to the Soil Testing Laboratory in 1967 from agricultural land in the Okanagan Valley had pH values at or below 6.0, by 1975 this percentage was found to be 23%, and nearly one-half of these samples were below pH 5.0 (50). In 1972, a survey showed that about 50% of the orchards had at least one sample with a pH value below 5.5 (62). The study concluded that soil acidity in the Okanagan was increasing and that fertilizers were the primary cause of this problem. Unpublished work by the University of British Columbia has found that many soil samples taken from irrigation drip lines are below pH 4.0 (personal communication, L. Lavkulich, University of British Columbia).

Small areas of acid-sulfate soils have been observed in the dyked floodplain soils of the lower Fraser valley and delta, where they have been drained for cultivation. The significance to agriculture of acidification in these soils is unknown at this time.

6.2 The Great Plains Region

Acidification appears to be most common in the Grey Luvisolic, Grey Brown and Black Chernozemic and Solonetzic soils of central and northern Alberta, the Peace River district of British Columbia and the northwestern area of cultivated land in Saskatchewan near Meadow Lake and Lloydminster. Although many of these soils developed on calcareous or saline parent materials, leaching of the surface horizons

Table 6. Approximate average annual contribution to soil acidity by atmospheric deposition (1977-79) and fertilizer use (1974-79) expressed as $CaCO_3$ equivalents required for neutralization (kg $CaCO_3$/ha per year).

Location	Atmospheric[1]	Fertilizer[2]	Total
Atlantic Provinces	30	84	114
Quebec	35	51	86
Ontario	33	90	123
Manitoba	5	72	77
Saskatchewan	0	12	12
Alberta	2	51	53
British Columbia	5	66	71
Mean	16	61	77

1. Based on estimated contribution of long-range transported acidity from precipitation calculated from: (H^+ + 1.15 (NH_4^+) - 0.7 (NO_3^-)); See Coote, D.R., Siminovitch, D., Singh, S.S., and Wang, C. 1981. The significance of acid rain to agriculture in eastern Canada. Res. Branch, Agriculture Canada. Local deposition from point sources such as smelters and gas plants are not reflected in these data.

2. Based on fertilizer sales data, Canadian Fertilizer Institute, assuming an average requirement of 3 g of $CaCO_3$ per g N (refs. 17 and 84) and expressed in terms of unit area of improved land. In some fields, contributions may exceed 500 kg/ha per year.

has left them depleted of calcium and other bases, and often with pH values below 6.0. A pH value below 6.5 is considered to present limitations for western Canadian agriculture (127).

These soils are susceptible to any increase in acidity from ammonium fertilizers and atmospheric inputs due to their low natural pH. Fertilizer use has been steadily increasing and tends to be highest in areas with relatively acid soils (50). The potential for further acidification from this source has been noted with alarm (84). Deep plowing has been practiced in some Solonetzic soils to bring calcium to the surface, but this is not practical in all areas (50), and is not currently recommended.

Although atmospheric acidity (H^+, NH_4^+) is generally low in western Canada, there is an area of higher atmospheric sulfur from the U.S. border to the Peace River district just to the east of the Rocky Mountains. This is due to the natural gas extraction activities of the region, whereby gaseous and particulate sulfur emissions enter the atmosphere during combustion and sulfur removal and from dust at sulfur storage areas. A simple prediction of soil acidification based on atmospheric sulfur deposition is not possible since much of the sulfur is deposited as neutral salts which do not cause acidity (81). However, reduced pH values have been attributed to atmospheric emissions from gas processing plants at least as far as 10 km downwind (50). The soil affected directly by windblown sulfur dust from sulfur stockpiles has been estimated to be less than 400 ha, but pH levels as low as 2.0 have resulted, requiring massive lime applications of up to 630 t/ha for correction (80).

In certain instances, such as in some Grey Luvisolic soils deficient in sulfur, atmospheric sulfur transport is beneficial (79). Unfortunately, the soils most deficient in sulfur are not located in the zones most affected by atmospheric sulfur deposition.

There is a problem of lime supply in the areas most affected by acidification. This is particularly disturbing in the Peace River district where transportation costs are high and lime is essentially unavailable at present. It is only slightly more available elsewhere in the affected area, and thus is not used to any large extent anywhere in the prairies.

Conservative estimates based on the current rate of acidification from fertilizer use, not including atmospheric fallout, indicate a need for over 350 000 t/year of lime just to maintain current pH levels (50). To restore pH values to approximately 0.5 units above their present levels will require more than twice this amount. About 25% of these requirements are for the Peace River district.

Acidification is not considered to be a problem at present in Saskatchewan south of the Meadow Lake - Lloydminster area, as fertilizer nitrogen use is relatively low and soils are high in exchangeable bases. Although fertilizer use is higher in Manitoba than elsewhere in this region, no acidification problems have been identified.

6.3 The Great Lakes - St. Lawrence Region

Little work has been done on acidification in Ontario and Quebec soils, but a potential problem exists because of high precipitation, large applications of nitrogen fertilizers and significant sulfur and ammonium deposition from the atmosphere. Soil acidification appears to be accelerating as a result of the large applications of fertilizer nitrogen used for corn production, and because of the northeasterly drift of polluted air from the industrial complexes of the Great Lakes States and south central Ontario and Quebec.

Land in the Great Lakes Basin portion of Ontario received an average of over 50 kg/ha of sulfate from the atmosphere in 1974, with some regions experiencing SO_4 rates as high as 95 kg/ha (1). These inputs are expected to continue at about the same rate up to the year 2000, even if sulfur removal at smoke stacks is made mandatory. If sulfur removal is not required, deposition rates will probably increase by about 2.5 times by the year 2000 (1), but this does not take account of possible increases in the use of coal for power generation. To neutralize the present average atmospheric input of acidity (sulfur and ammonium) across the agricultural part of the region would require $CaCO_3$ at approximately 30-40 kg/ha per year or about 1 t/ha of limestone every 25 years.

The acidification of lakes in the Canadian Shield has received much attention recently, but little work has been done on increased acidification of soils in this region. In an area east of Sudbury, downwind of a nickel smelter, average pH values of 3.7 in the surface soil within 3.5 km of the plant have been recorded (95). These have been attributed to sulfur emissions.

In some cultivated Ontario soils current research suggests that high fertilizer use, coupled with increased leaching due to accumulation of runoff in some cases, has led to increased soil acidity and reduction of crop yield (85). The extent of this problem, however, is unknown. Many surface soils of fields in southwestern Ontario have been found to contain areas with pH levels as low as 3.4 to 4.0. These values are almost always associated with sandy soils, monoculture corn cultivation and high nitrogen use for a number of years; magnesium deficiency appears to be the first visual symptom of the problem (personal communication, C.S. Baldwin, Ontario Ministry of Agriculture and Food, Ridgetown). Similar problems have been identified in sandy soils used for corn and potatoes in south central Ontario even though some are quite calcareous below the surface horizons. Some sandy Podzolic soils in Quebec have shown a tendency for reduction in pH after 25 years of light cultivation. This effect was not observed in finer textured Gleysolic soils in the same region (67).

Lime use in Ontario has been steadily increasing for the past 35 years, but is low compared with Quebec and compared with inputs of atmospheric and fertilizer acidity. It is estimated from quarry sales data[1] that improved land in Ontario received $CaCO_3$ at an average annual rate of about 25-30 kg/ha between 1975 and 1977. This is only 20-25% of that required to neutralize atmospheric and fertilizer acidity. In general, Ontario soils are developed on moderately calcareous parent materials and are therefore fairly well buffered against increased acidity because of their neutral pH values and high cation exchange capacity. It may therefore be many years before the short-fall in liming results in pH problems. On sandy soils, however, especially those used for highly fertilized crops like corn and potatoes, these problems are already becoming evident. In Quebec, lime use averages about five to six times that of Ontario[2] while atmospheric and fertilizer acidity is lower. Even though many Quebec soils are less well buffered than those of Ontario, the present liming practices appear, on average, to be keeping pace with accelerated acidity.

6.4 The Atlantic Region

Acidity is an inherent feature of many of the Atlantic region soils, as high rainfall and low evapotranspiration ensure considerable soil leaching. Where high levels of nitrogen fertilizers are used, the potential for accelerated acidification is present. In New Brunswick and Prince Edward Island, where large areas are used for potatoes, acidification has not been a problem for this crop but it interferes with the growth of other crops in rotation. This is of concern considering the need for rotational cropping for soil erosion control.

Little information on accelerated soil acidification is available for most of this region. However, in Prince Edward Island soil test data show a distinct trend for pH values to be lower in 1977 than in the previous 5 years, but the reason for this has not been established (123). There was a trend for samples submitted by farmers planting potatoes, tobacco, and corn to have lower pH values than those submitted before planting forages and cereal grains. While the data are inconclusive they suggest that farms with less rotational cropping and more monoculture have more acid soils.

There is evidence of moderate atmospheric acidity in the Maritimes due to the prevailing southwesterly winds, in spite of the relative remoteness of this area from industrial concentrations. There are also potential localized problem areas near generating plants and coal-burning industries, such as in the Bathurst region of New Brunswick and parts of Cape Breton Island.

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[1] Energy, Mines and Resources Canada, Mineral Policy Branch, Ottawa, "Limestone used for agricultural purposes". Unpublished data, 1975-77.

[2] Les Producteurs de Pierre à Chaux du Québec, Inc., Verdun, Québec. Unpublished data 1974-78.

Lime use is common in the Atlantic region. The average annual applications of limestone to improved land in Nova Scotia, based on county data,[1] ranged from 390 to 4026 kg/ha between 1975 and 1978; in New Brunswick they ranged from 220 to 1853 kg/ha (1977 to 1979).[2] In Prince Edward Island average application rates were about 260 kg/ha annually between 1975 and 1980,[3] and in Newfoundland, regular applications of up to 4000 kg/ha are common. These values are all in excess of the average combined fertilizer and atmospheric acidity requirements but since the soils are developed on noncalcareous parent materials and tend to be coarse textured and low in organic matter, they are poorly buffered against acidity. They commonly require frequent lime applications if excessive acidity is to be avoided.

Marine soils high in sulfates are found locally in some of the dyked coastal estuaries and floodplains near the Bay of Fundy in New Brunswick and Nova Scotia, but the extent of any problem areas is not clear. Data from New Brunswick (97) show that in soil dyked for 8-12 years, pH values as low as 4.5 to 5.2 were found in the top 30 cm, compared with pH 6.4 to 7.1 in recently dyked land. This may be due to leaching of salts from the surface horizons and to acidification because of sulfur oxidation. In soils dyked more than 50 years ago, pH values ranged from 5.6 to 5.8 in the top 30 cm, presumably due to leaching of sulfates from the soil profile.

7.0 SOIL CONTAMINATION

Soil contamination is considered here to be the deterioration of soil quality due to chemical additions other than the salts, sulfur and nitrogen discussed under salinization and acidification. It includes other aspects of atmospheric fallout, sewage and industrial sludge disposal, pesticide residues and biological contamination.

Radioactive fallout and persistent residues of the organochlorine pesticides are not discussed in detail because both are uncontrollable and appear to be declining to below tolerable levels. The rate of radioactive fallout (of strontium 90, for example) peaked around 1965-66, and is now declining by natural decay (21). Without further atmospheric testing of nuclear weapons, or a nuclear catastrophe, these levels should continue to decline. There is no known practical method by which present levels can be reduced, and crop uptake has been found to be below limits required by health standards (21). As far as is known, wastes from generating stations are not currently being disposed of in a manner that affects agricultural land.

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[1] Nova Scotia Dept. of Agric. and Marketing, Agriculture Statistics, 1978, p. 72.

[2] New Brunswick Dept. of Agric and Rural Ind. Agriculture Statistics, 1977-79.

[3] Personal communication, R. Vinot, P.E.I. Soil Test Lab, Charlottetown.

The use of aldrin, dieldrin and DDT was discontinued between 1969 and 1972, and the use of such insecticides as chlordane, heptachlor and endosulfan has been greatly restricted (43). A great deal of information has been gathered on the fate of persistent organochlorine pesticides in soils. Levels of these compounds are declining through biologic decomposition. However, decomposition rates are affected by soils and climate, being higher in warmer, moister and coarser textured soils than in cooler, drier and heavier textured soils (38, 45, 110).

At normal application rates, few herbicides persist in the soil at phytotoxic levels for more than a year (4). However, cool climates and clayey soils also delay herbicide decomposition, while some herbicides, such as paraquat, are so tightly bound to soil clay particles that decay is almost halted, resulting in possible buildup (61).

The considerable awareness of potential environmental problems with pesticides, together with the intensive evaluation process required before they can be registered for use, has reduced the extent of soil contamination by pesticide residues. However, reactions of pesticides with soils remain an important consideration and continued vigilance and monitoring are warranted.

Biological contamination is a complex problem, which includes such organisms as the golden nematode in Newfoundland and Vancouver Island, as well as a number of other soil-borne disease organisms such as clubroot in cabbage and root rot in cereals and tobacco. Animal parasites and diseases such as coccidiosis of poultry and anthrax in cattle can also be transmitted by the soil and soils can become contaminated by the organisms involved (21). However, survival of most parasitic and disease organisms is for relatively short periods, and proper management of livestock and pastures can prevent reinfection. There does not appear to be any land in Canada currently restricted from livestock production due to soil contamination by disease organisms.

Other forms of biological contamination can also be mentioned. Roots or residues of previous crops leave exudates or decomposition products in the soil which are toxic or antagonistic to succeeding crops. An example is the interference by wheat or rapeseed residues with germination of a following wheat crop. This type of soil degradation is controllable by proper crop rotation and management.

7.1 The Cordilleran Region

Few problems of contamination have been observed in British Columbia. Atmospheric deposition of heavy metals such as lead and zinc may be occurring in the Trail region but there have been reductions in emissions in recent years. This area is also almost entirely forested.

Industrial wastes are not a common problem in British Columbia as extensive manufacturing exists only in the Vancouver area. Sludges from sewage treatment at Vancouver are dried and landfilled, or incinerated or stored (12). Sewage treatment is becoming more common in the interior urban areas to protect lakes from pollution and this has led to problems with disposal of effluents and sludge. Spray irrigation of effluents and drying of sludge followed by disposal on land are often practiced. Agricultural land and parkland have been used for sludge disposal, and at Kelowna some composting has been done.

Waste from the fruit and vegetable processing industry contains sodium, is very alkaline in reaction and can contaminate soils if disposal is not properly managed. Large volumes of manure are sometimes spread on small areas of land, especially near Vancouver where land availability is limited. This can result in excessive nutrient inputs and possible metal contamination.

The production of orchard and vegetable crops in parts of British Columbia for extended periods has resulted in accumulations of some pesticide residues in these soils. Arsenic, lead and copper were associated with the pesticides used before the organochlorine compounds came into prominence in the 1950's. Such residues have been found in orchards in the Okanagan Valley, but it is considered unlikely that they have accumulated to toxic levels because they were removed from the market at the first signs of contamination as early as 1938 (41). Some high boron residues that have been encountered are attributed to buildup of boron applied to correct a deficiency in soils of this area (86).

7.2 The Great Plains Region

Waste disposal could become a problem in the vicinity of large cities, and contamination could occur if industrial wastes are included in sludges spread on land. Edmonton currently stores sludge, with long-term plans to use it as a "soil conditioner" or place it in landfills. Calgary stored sludge until 1976, when land application was initiated. Yorkton, Regina and Saskatoon have all applied some sludge to farmland. Winnipeg disposes of sludge on farmland without restrictions (including winter spreading on frozen soils), though forage growing is discouraged where sludge is applied (12, 126). Waste disposal is also a problem for scattered small communities with insufficient lagoon capacity and poor disposal practices (21). Municipal waste water is used for irrigation in many of these communities.

Soil contamination problems are associated with spills from oil pipelines in Alberta and Saskatchewan. Some soil damage from spills and burning of crude oil near oil wells has also occurred (21). Soils contaminated by light oil spills can recover within 4 years with cultivation and fertilizer applications (72). Some soils have also been contaminated by wind-blown dust from mining activities.

Although insecticide residue problems are not likely because of very limited use, there is some concern about the wider acceptance of minimum and zero tillage and the associated increase in herbicide use.

7.3 The Great Lakes - St. Lawrence Region

The Great Lakes - St. Lawrence region is the one most threatened by soil contamination. It is exposed to considerable quantities of atmospheric pollutants from within the region as well as from the U.S. industrial heartlands. There are considerable volumes of urban and industrial wastes for disposal, because the strict pollution control standards relative to the Great Lakes have resulted in urban and industrial waste treatment in southern Ontario which is more complete than elsewhere in Canada. Consequently, much sewage sludge is being spread on farmland, a practice that is likely to increase as landfill sites become more scarce. This region also has the highest density of industrialization and urban population in Canada, resulting in considerable waste production. Fuel consumption is also high, as are atmospheric (lead) emissions. The intensive fruit and vegetable production in the area has also led to greater use of pesticides than in other regions.

Approximately 11 100 ha of farmland in Ontario were used for sewage sludge disposal in 1975, all within 40 km of the city that produced the sludge (126). In 1978, 34% of Ontario's sludge was disposed of in this manner, the remainder being mainly incinerated (41%) or land-filled (16%). With possible increases in the degree of phosphorus removal at sewage treatment plants to meet the requirements of the revised U.S. - Canada Great Lakes Water Quality Agreement, it is likely that the quantities of sludge to be disposed of will increase still further. Since land used for sludge disposal should not be re-treated with sludge for a number of years to avoid heavy-metal buildup, the total area involved may be five to ten times greater than the area used in any particular year.

Land disposal of sewage is not practiced in Quebec at this time as, in general, large urban centres like Montreal still do not have facilities for complete sewage treatment. Discharge is directly into the St. Lawrence River and its tributaries.

Sewage sludge is a valuable source of nitrogen and phosphorus for crops. Studies in Ontario show that crop uptake and leaching losses of heavy metals are small (126). This indicates that these metals are accumulating in the soils to which sludge is applied. Of concern are mercury, cadmium, arsenic, lead, chromium, nickel, copper and zinc, all of which are retained by the soil as organic compounds and chelates following sludge applications (10). Continual incremental buildup could lead to eventual toxicity to plants and perhaps to livestock or humans, but these critical levels are not known. To date, some sludges have been declared unacceptable for land disposal because of cadmium content (126). The Ontario Ministry of the Environment has prepared guidelines for sewage sludge disposal designed to prevent excessive heavy-metal buildup in the soils to which it is applied.[1]

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[1] Ontario Ministry of the Environment, Pollution Control Branch, "Guidelines for Sewage Sludge Utilization on Agricultural Lands", Preliminary Draft, April 1978.

Many Ontario soils used in the past for orchards and vegetables (especially potatoes) have slightly elevated levels of arsenic, copper, mercury or lead, or a combination of these, attributed to past use of pesticides and top-killers (44). Consequently, sludge disposal on these soils may be more hazardous than on others. Organic soils used for vegetable production have the capacity to accumulate considerable quantities of heavy metals from pesticide use, or from micronutrient additions to correct deficiencies. The latter has been documented in the case of copper (44).

The large portion of the region used interchangeably for crops such as corn and soybeans also presents a problem with the carryover of herbicides such as atrazine. The atrazine may damage succeeding crops, but this is generally a temporary form of soil contamination and can be avoided by careful selection of herbicides combined with proper attention to crop sequence.

Fluorine contamination of soils has been noted in the Lac Saint-Jean area of eastern Quebec, and appears to be the result of fallout from aluminum smelting (21). Fluorine contamination of soils of Cornwall Island in eastern Ontario has allegedly also appeared downwind of an aluminum smelter, and is suspected of causing deterioration of livestock health. Soil pollution by cobalt, copper and nickel from industrial fallout has been noted in the vicinity of a cobalt-nickel smelter in Ontario (44), and by Ni, Cu, Zn, Fe and S near a nickel smelter in the Sudbury area (95). The same contamination process is suspected from the Noranda-Rouyn smelting complex in Quebec. PCB in agricultural streams in Ontario has been attributed primarily to atmospheric fallout from distant sources and local electrical transformers (43).

7.4 The Atlantic Region

There have been few soil contamination problems identified in this region. Sewage sludge is not produced in large volumes as most treatment plants have only aeration systems, and most effluent is discharged to the sea. Soil contamination from atmospheric inputs from lead, zinc, iron and silver smelting in New Brunswick is being evaluated.

Soil contamination from residues of pesticides and vegetation control chemicals is of concern. Sodium arsenite has been used widely in New Brunswick and Prince Edward Island potato fields as a top-killer prior to harvesting, and arsenic residues persist in some soils. In orchard soils of Nova Scotia, lead and mercury residues are detectable and attributed to past pesticide use (21).

In Prince Edward Island a problem has been identified with the disposal of lye waste from potato peelings, which has a high sodium content and pH greater than 10.0. Land adjacent to disposal areas has also been affected by contaminated runoff.

8.0 SOIL MIXING AND DISTURBANCE

Removal of soil overburden for the extraction of underlying minerals, coal or other materials results in considerable disturbance and land degradation. This may be due to mixing of soil before it is replaced, failure to replace the soil, or because of alterations of microtopography, surface or groundwater hydrology or other physiographic characteristics of the site. All of these can render land less suitable for crop production. The most obvious examples of such degradation are strip mining, sand and gravel extraction, and pipeline and drainage construction.

8.1 The Cordilleran Region

Soil disturbance in the Cordilleran region is most widely associated with forest and mining operations. Agricultural lands are seldom affected by these activities.

Soil disturbance and mixing occur in agricultural areas when pipelines and drainage works are installed, notably in the lower Fraser valley. At least 14 500 ha of land in this region have been used for sand, gravel and stone extraction (66). It is not known how much of this was used previously for agriculture, but current licensing procedures give preference to operations located on nonagricultural land.

8.2 The Great Plains Region

The main soil disturbance is associated with the energy industry in coal mining, oil and gas exploration and pipelines; and sand, gravel and stone extraction. Other mining activities, such as for potash, salt, gypsum, and silica result in relatively small areas of agricultural soil disturbance.

Strip coal mining in the plains of Alberta and Saskatchewan currently covers about 6800 ha, with about 500-650 ha being stripped each year (115). In this area approximately 340 to 690 ha, most of the area of new strip mines, is being reclaimed each year.

Projections of future demand indicate that, in Alberta alone, by the year 2004 about 5670 ha of plains area will be mined each year (47). Between 1975 and 2004, it is estimated that nearly 69 000 ha will have been mined. Coal mining in Alberta currently affects more foothills land (3150 ha) than plains area (2340 ha), but about 80% of this province's shallow coal deposits are beneath Chernozemic and Solonetzic agricultural soils (115). The time between initial disruption of agriculture and the completion of primary reclamation is about 5 years, indicating that by 2004 over 28 000 ha will be idle at any one time (47). Reclamation of these soils after mining is uncertain. Differences in opinions exist as to the value of topsoil removal and return, and the depth and degree of soil mixing for optimal salinity control. Changes that may occur in the quality or depths of saline groundwater during and after strip mining are also of concern. It takes about another 5 years after reclamation before land is returned to an acceptable productive state.

Sand, stone and gravel extraction in Alberta, Saskatchewan and Manitoba covers approximately 30 000 ha, distributed almost equally between the three provinces (64, 66, 115). Land affected by oil and gas drilling in Alberta amounts to almost 10 000 ha, while that taken up by brine ponds and tailings associated with the potash industry totals about 2000 ha.

Many oil and gas pipelines cross the region but many prairie soils, and Solonetzic soils in particular, do not appear to be seriously impaired by pipeline construction (32, 118). Improved structure of the Bnt horizon and some salt redistribution by soil mixing during trenching and backfilling may account for increased yields on Solonetzic soils over some pipelines. However, many soils in the northern prairies may be adversely affected, especially where construction proceeds under wet conditions. There are approximately 5000 km of major oil and gas pipelines in the Prairies (76), but there are also many small feeder lines.

8.3 The Great Lakes - St. Lawrence Region

Some gypsum, silica and salt are mined in the Great Lakes - St. Lawrence region, but generally there is little mining activity in agricultural areas. Asbestos is mined in the Eastern Townships of Quebec, but the sites do not involve large areas of high-capability agricultural land.

Sand, gravel and stone extraction is extensive, amounting to at least 67 000 ha (66). It is not known what portion of this area involves prime farmland, but in Ontario, 90% of this extraction activity is in the southern part of the province where urban centres are located. In the area of Kitchener to Oshawa almost 50% of the aggregate land reserves are classes 1 and 2 agricultural soils (personal communication, E. Presant, Agriculture Canada, Guelph). The potential impact on agriculture of aggregate removal is of concern because it is unlikely that this land can be restored to its original level of production potential. About 30% of the sand and gravel extraction areas of southern Ontario have received some form of reclamation treatment (66). Sand, gravel and stone pits cover about 25 000 ha in southern Quebec (66), and there are similar concerns about reclamation.

Pipelines cross the region as far east as Montreal and extensions are planned to Quebec and possibly into the Atlantic provinces. Many such pipelines cross high-quality agricultural land, and depending on methods and weather conditions at the time of construction, they have varying impact on the soil and on subsequent productivity. In soils underlain by stony till or bedrock, stones may be brought to the surface and become a problem after construction. In most soils, mixing of topsoil with subsoil material leaves lower fertility and poorer structure. Careful construction techniques, using topsoil removal and return over the trench and preventing the spread of subsoil from the trench over the work area, reduces these problems. Less readily overcome, however, are the problems of compaction, rutting and soil mixing over the entire work area which occur when construction is carried out under adverse weather conditions (101).

Yield reductions have been observed for at least 4 years after pipeline construction. In one study in southern Ontario (31) corn yields over the trench and work area were only 42-43% of those of the adjacent field in the 1st year after construction. Four years later the yields were 74% over the trench and 86% over the work area. Soybeans and cereal yields were less affected during the 1st year than were corn yields, and sandy soils were less affected than clay or loam soils. Organic matter levels, soil porosity, soil hydraulic conductivity and soil tilth were all adversely affected by pipeline construction in areas suffering yield reductions. These data pertain to pipeline construction when soils were wet, but at other sites where construction was done under dry conditions or when the soil was frozen to at least the 20-cm depth, there was little effect on productivity.

Surface and subsurface drains are common in the Great Lakes - St. Lawrence region. During construction and cleaning of surface outlet drains, large quantities of subsoil spoil must be disposed of and are frequently spread on adjacent land. Results are similar to those following pipeline construction. Compaction and rutting from vehicles is likely if the spoil is hauled away. The installation of subsurface drains involves methods similar to those used for pipelines, except that the trench and the machinery are usually smaller. Alternative procedures, such as continuous plastic drains installed with a "plow", create little disturbance and minimal compaction if conditions are dry.

In recent years approximately 1300 km/year of new or reconstructed ditches have been excavated in Quebec. In Ontario, where drainage improvement has been more intensive for a longer period, new ditches are being constructed at approximately 170 km/year in addition to regular reconstruction work. The length of subsurface drains in Canada was estimated at 660 000 km in 1975 and has been increasing steadily, especially in Quebec (22). However, the improved soil drainage after installation generally more than offsets any damage to the soil during construction, and with improved equipment and techniques, soil disturbance problems should be minor.

8.4 The Atlantic Region

Soil disturbance by mining and pipelines affects only small areas of agricultural land, but sand and gravel extraction is a concern throughout the Atlantic region. The possible extension of oil pipelines to Fredericton and Halifax may create problems where farmland is crossed. The nature of the dense, stony subsoils which are common in this region suggests that problems with soil structure and stoniness may be encountered after these pipelines are constructed.

Surface drainage outlets are extensively constructed throughout the agricultural lands of the region, creating spoil disposal problems as discussed earlier. Tile drainage is not yet extensive but it is increasing with the expansion in corn production, which is particularly sensitive to even short periods of saturated soil conditions.

9.0 DETERIORATION OF DRAINAGE SYSTEMS AND FLOODING

One form of drainage deterioration is manifested by the plugging of tile drains with material of microbial "iron ochre" origin or with fine sediments, often combined with so much deterioration of the soil structure that infiltration is reduced to the point where the drainage system no longer functions efficiently. Another problem is that of deterioration of outlet drainage networks so that water cannot leave drained areas efficiently.

The problem of plugging of drains appears to result from a more or less uncontrollable microbiological and chemical process of iron and manganese oxidation, precipitation of amorphous material on tile and filter surfaces and eventual reduction of rates of water flow into the tile (52). It has been reported in southern Ontario in sands and organic soil underlain by sands (52), and also, in one instance, in a heavy clay soil (91), but occurrences are widely scattered and somewhat unpredictable (105). In eastern Ontario, it has been observed in coarse textured soils. It has also been reported in Quebec and the Maritimes, but no estimates are available from other parts of Canada. The problem may seriously impair drainage systems within 2 years of installation and no practical solutions are available (52). Excavation of affected tile, cleaning and replacement with a gravel backfill leading to a blind inlet at the surface appears to be the most feasible corrective measure (104). If the area involved is extensive, it may be more economical to retile the area using gravel backfill.

Plugging of tile drains with sediments is a problem in fine sandy and silty soils. In practice, it is generally avoided by wrapping tile with a filter material and/or by constructing drains with sufficient gradient to prevent the deposition of sediments in the pipe. The latter has the disadvantage of increasing stream sedimentation below the tile outfall.

Problems of outlet drainage deterioration can occur almost anywhere in Canada. Most of the controls involve design of drain cross-sections for stable banks in different soil types and groundwater conditions; protection from erosion of culverts, grade changes and sharp bends; and maintaining channels and debris traps. Farmers can aggravate problems by cultivating too close to drains, allowing cattle free access to wet drain banks and allowing soil erosion to occur in fields which contribute sediments to drains.

No estimate is available of the area of farmland affected by flooding due to deteriorated drainage systems. However, the lower Fraser valley, the Peace River and Foothills districts, the northern prairies, the Red River valley and almost all Ontario and eastern Canada rely heavily on surface drainage systems to prevent flooding of farmland. The systems need superior design, which has until recently been lacking, protection and constant maintenance to keep them functioning efficiently. Reconstruction or major maintenance after 7 to 10 years is not uncommon. The usual cause is bank erosion and channel sedimentation.

10.0 SUBSIDENCE OF ORGANIC SOILS

Organic soils are common in all regions of Canada, but they are not used to any great extent for agricultural production except in a few locations. When they are drained, usually for intensive cultivation of high-value crops, drying and oxidation occur and the mass of soil material begins to contract due to shrinkage and loss of carbon, and to increase in density due to humification. Shrinkage occurs also due to reduced moisture content and capillary forces, loss of buoyant forces present in the saturated state, compaction by machinery, and wind erosion (51). Depending on tillage and moisture conditions and type of organic material, the total subsidence rate is high in the first few years after drainage, and then declines. In some cases organic soils are also lost by deliberate or accidental burning.

In the Holland Marsh of southern Ontario, post-drainage subsidence rates were measured at about 3.3 cm/year between 1959 and 1962, following drainage improvements made in 1957 (51). Between 1967 and 1976, they were estimated to be about 1.1 cm/year, which was the same as the estimated rate prior to drainage improvements. The installation of subsurface drains may have reduced the life of these soils by 35 years. In Quebec an estimate of subsidence in an organic soil area cultivated for vegetable production was 2.1 cm/year over the first 38 years of cultivation. Based on this rate, it was predicted that the soil would be no longer usable after another 44 years (74). While this may underestimate the useful life of the soil because of the more rapid rate of subsidence that occurs during the first year or two after drainage (71), it is interesting to note that the Holland Marsh in Ontario is expected, by some extension specialists, to last about the same length of time.

Elsewhere in Canada, organic soils are used for vegetable production in the lower Fraser valley of British Columbia, and in New Brunswick, Nova Scotia and Newfoundland. Estimates of subsidence rates are not available for these areas, but it is suspected that the soil loss in British Columbia may be higher than the others due to lack of freezing.

Organic soils are still being cleared in Manitoba, mostly for hay and pasture, as they have been elsewhere in the northern prairies. In many cases, however, they are considered to be undesirable and are burned extensively (73). No control of water tables or burning appears to be practiced in Manitoba in order to preserve these soils, though the burning is now restricted for environmental reasons.

In effect, productive organic soils are being "mined" by drainage and cultivation. Proper control of water tables, by maintaining as high a water table as possible whenever vehicles are off the soil, will reduce subsidence rates. This generally requires carefully engineered dykes, ditches, drains and pump systems. While these are generally available for drainage, there is little attempt in Canada to use these systems in an integrated water-table management program to minimize subsidence.

Soil subsidence rates may also be reduced by the inhibition of the bacterial and enzyme activity through which oxidation occurs. Studies in Newfoundland and Quebec have demonstrated that copper, originally added as a fertilizer supplement to correct for deficiencies in some organic soils, has the effect of inhibiting oxidation of carbon, and thus reduces subsidence rates (70). Further research is under way to examine the practicality of applying copper to organic soils as a mitigation measure to reduce subsidence from biochemical oxidation.

Organic soils of the lower Fraser valley, southern Ontario, the St. Lawrence and parts of the Maritimes are most valuable for agriculture because of climate. Many of these have already been developed, generally with little regard for subsidence control. Where organic soils are intensively managed, such as in southern Ontario and Quebec, the remaining life of much of this resource is probably less than 100 years. In other areas, lack of interest, concern or forethought appears to be resulting in rapid destruction and inadequate exploitation of these soils.

11.0 EARTHFLOWS AND LANDSLIDES

Many soils will flow or slide when conditions of water table, vegetation or slope cause instability. It is a major part of the soil erosion problem in logged mountain forests, where steep mountain slopes fail due to disturbances such as road or railway construction. The Ottawa valley/ St. Lawrence area (together with an area near Lac Saint-Jean in Quebec and a small portion of the lower Saint John River valley in New Brunswick) and the river valleys of the Upper Cretaceous prairie landscape of western Canada are the main regions where agricultural land can be affected by landslides or earthflows. The former area is associated with the marine (Leda or "quick") clay deposits which, given certain moisture and loading conditions, become fluid when disturbed and may flow under the influence of gravity. When hydrologic conditions are altered, or when slope angles are undercut by river bank erosion or highway construction, large volumes of soil may be lost in these earthflows. In 1971, an earthflow in eastern Ontario resulted in 30 ha of pasture land flowing 2-4 km down the South Nation River, while in the same year 31 people were killed when 27 ha near Lac Saint-Jean flowed into a tributary of the Saguenay River (114). Such extreme events are infrequent, but small slides affecting farmland, highways and occasionally residences occur almost annually. Avoidance of disturbance of these soils by adequate land-use planning could probably reduce the losses incurred from such earthflows.

The situation on the Prairies is different but is common to major river valleys such as the North and South Saskatchewan, Qu'Appelle, Bow, Old Man, and Peace. Most landslides in these areas are old and inactive, having originally been caused by downcutting of the rivers. These lands are currently used mostly for pasture or rangeland, but the slides can be reactivated by changes in water tables due to seepage from irrigation canals and the construction of dams. Excessive runoff and erosion in the river channel itself also cause reactivation of slides (116). The most susceptible areas are shale materials of marine origin. In 1973, an earthflow temporarily dammed the Peace River, between Hudson Hope and Fort St. John, with alluvial clay material, resulting in flooding of agricultural land in the valley bottom.

12.0 SUMMARY AND CONCLUSIONS

Degradation of agricultural lands to varying degrees is a widespread phenomenon in Canada. It manifests itself in many forms and processes. Every province and almost every soil type is subject to one or more forms of degradation. If not suffering active degradation, many soils have the potential to do so if management is inadequate. The weight of evidence supports the concept of a situation in which most cultivated soils are deteriorating by at least one process, but where this deterioration is often masked by the temporary benefits to productivity of management practices which themselves may be contributing to the problem over the long term. In certain cases soils with superior management are improving in quality, but these areas are not extensive.

Many soil degradation problems are distributed regionally. Often more than one process is active simultaneously within a field. In eastern Canada, for example, soils may be found which have been used for monoculture row crops for over 20 years, have been repeatedly tilled and driven on when wet with ever-larger machinery, have been heavily fertilized and treated with pesticides, and in some cases have also been used for sewage sludge disposal. The whole area is also subjected to relatively high levels of atmospheric pollutant fallout. Not surprisingly, soil erosion, compaction, acidification and contamination are major concerns in this area. Farmers worsen the problems by removing fencerows and plowing up and down slopes in the fall.

In western Canada, on the other hand, farmers are concerned about salinization, organic nitrogen and wind erosion. Summerfallow is still widely practiced even where moisture levels do not make it necessary. Weed control, nitrogen availability, economics and tradition all influence the cropping decisions that relate to these soil quality concerns. Some land now developing problems has been treated in much the same way for generations, indicating the latent nature of some of the processes involved.

Interestingly, there are soil degradation processes that receive little attention because they are not expected. For example, water erosion in the west and wind erosion in the east appear to be considerably more important than generally recognized. Acifidication and liming are also better understood in the east, where the problem has long existed, than in the west where it is now developing in certain soils as a result of nitrogen fertilizers and local atmospheric sulfur emissions.

Some soil quality problems are not regionally distributed. Extraction of gravel, for example, destroys agricultural land in all regions yet reclamation is, at best, uncertain. Energy-related activities such as coal mining and pipeline construction are becoming a national concern, and have potential to affect far larger areas in years to come. Contamination of the disturbed soils further compounds reclamation problems.

Some soil degradation problems initiate or aggravate others. For example, where crop growth is stunted or destroyed by salinity or contamination, the soil may become affected by wind or water erosion; excessive tillage under wet conditions may damage soil structure and reduce the effectiveness of drainage systems, which results in more frequent working of the soil when wet.

Consideration must be given to the question of how long these conditions can continue before amelioration will be possible only through the input of large amounts of chemicals and energy in order to maintain yields. And then, what will be the cost of obtaining those yields, and how reliable will the soils be under periods of unfavourable climate? What effect will this have on the cash flow problem at the farm level?

Unfortunately, these questions cannot be answered with certainty. In most cases of land degradation remedial management is known and understood but short-term economics, traditional attitudes and the lack of convincing data encourage the situation to continue unchecked. New and innovative research is needed in areas such as saline seep prevention, control of erosion, quantification of changes in soil structure, and the diversification of uses for legume forages. A large part of the solution depends on the development of innovative policies and programs at different levels of government aimed at providing assistance at the farm level, where most of the control work will have to be done. A situation must be reached where scientists, specialists, extension workers, the farming community and the public at large are made aware of the present and potential problems as well as the alternatives for their control. The eventual aim must be a state of land stewardship that maintains the land resource in an optimal or best possible state for agricultural production relative to the regional climate of the area. The alternative is short-term economic gain, but a long-term, non-redeemable mortgage on the future.

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