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Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators

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Abstract

Tillage has been and will always be integral to crop production. Tillage can result in the degradation of soil, water, and air quality. Of all farm management practices, tillage may have the greatest impact on the environment. A wide variety of tillage equipment, practices and systems are available to farmers, providing opportunities to enhance environmental performance. These opportunities have made tillage a popular focus of environmental policies and programs such as environmental indicators for agriculture.

This paper provides a very brief examination of the role of tillage in crop production, its effect on biophysical processes and, therefore, its impact on the environment. Models of biophysical processes are briefly examined to demonstrate the importance of tillage relative to other farm management practices and to demonstrate the detail of tillage data that these models can demand. The focus of this paper is an examination of the use of information on tillage in Canada's agri-environmental indicators initiative, National Agri-environmental Health Analysis and Reporting Program (NAHARP). Information on tillage is required for several of the indicators in NAHARP. The type of data used, its source, and its quality are discussed. Recommendations regarding the collection of tillage data and use of tillage information are presented.

Keywords: Tillage; Soil management; Environmental indicators; Soil erosion; Tillage erosion; Crop residue cover

1. Introduction

Tillage has been and will always be integral to crop production. Tillage has many roles in crop production, including seedbed preparation, seed placement, incorporation of nutrients and other amendments, and management of water and pests. Tillage also affects a variety of biophysical processes that impact the environment. These processes include: wind, water and tillage erosion, leaching and runoff, pesticide sorption and degradation, greenhouse gas emissions and soil carbon sequestration. Consequently, tillage has direct and indirect impacts on water, soil and air quality.

1.1. Objective

The objective of this paper is to demonstrate the importance of tillage as a farming practice, both in terms of crop production and environmental impacts, and to demonstrate the need for detailed and accurate data on tillage practices. The focus of this paper is an examination of the use and associated limitations of information on tillage in Canada's agri-environmental indicators initiative, National Agri-environmental Health Analysis and Reporting Program (NAHARP).

2. Importance of tillage

2.1. Tillage and its role in crop production

Tillage includes all field operations whereby soil is engaged by tools and is consequently disturbed. "Tillage

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is the manipulation, generally, mechanical, of soil properties for any purpose; but in agriculture it is usually restricted to modifying soil conditions for crop production" (Soil Science Society of America (SSSA), 1987). "Tillage equipment includes any field tools and machinery which is designed to lift, invert, stir, and pack soil, reduce the size of clods and uproot weeds, i.e. ploughs, harrows, discs, cultivators, rollers, etc." (SSSA, 1987). Hence, a broad suite of farm management practices involves tillage, much broader than is commonly thought of as tillage practices. Although the definition of tillage presented may not seem practical for some purposes, it is the accurate definition and is supported by scientific and engineering communities, and it is considered necessary to fully and accurately understand the impacts of farm management practices on agricultural production and the environment.

Tillage has many roles in crop production (Cornish and Pratley, 1987; Titi, 2003). The most widely recognized function of tillage is seedbed preparation. In traditional, mechanized crop production systems seedbed preparation consists of several field operations: mouldboard ploughing to turn the soil, breaking sod, incorporating crop residues, aerating and warming the soil; disking to break large clods, cut sod and crop residues, pack soil and smooth the surface of the land for subsequent field operations; and harrowing to further smooth the surface by breaking clods and mixing soil. This form of seedbed preparation is commonly referred to as "conventional tillage". However, a variety of forms of seedbed preparation exist, many of which are referred to as "conservation tillage" because they use fewer and less disruptive tillage operations for soil erosion control (often, this is achieved by replacing the mouldboard plough with a chisel plough, disc plough, blade plough or sweep plough). Seed placement requires some form of tillage; even in so-called "no-till" or "zero-till" crop production systems, the soil must be disturbed to place the seed. Tillage has been used for thousands of years to release nutrients from the soil through accelerated mineralization of organic matter and to incorporate nutrients found in manures and crop residues. More recently, equipment has been developed to inject manures, commercial fertilizers and other amendments into the soil. Tillage has been used extensively in the past to control weeds, insects and diseases, largely through residue management. The recent development and use of commercial pesticides has greatly reduced the use of tillage. The widespread adoption of no-till/zero-till systems in North America has been largely attributed to the availability of cost-effective glyphosate for weed control. It is reasonable to assume that if general pesticide use was limited or eliminated there would almost certainly be a return to more intensive tillage. Tillage is also used to manage soil moisture (e.g. hilling row crops) and soil structure (breaking up soil crusts and alleviating soil compaction). Possibly the most spectacular example of a farm management practice which is not thought of as tillage but results in significant soil disturbance is the harvesting of root crops such as potatoes and sugar beets.

The suite of tillage equipment and practices that characterize the method of crop production constitute a tillage system. The method of tillage is often integrated into descriptions of cropping systems, e.g. no-till corn-soybean production.

2.2. Tillage and the environment

Tillage, by affecting crop production, affects the environment: crop productivity affects the production and consumption of CO_2, the production of biomass above and below ground, the uptake of soil water and its transpiration, and the efficiency of cropping inputs such as fertilizer and pesticides. In addition to its effects on crop production, tillage also affects a variety of soil biophysical properties and processes that impact the environment. It affects wind, water and tillage erosion, leaching and runoff, greenhouse gas emissions, pesticide sorption and degradation, as well as other biophysical processes. Tillage, by affecting the amount of crop residue on the soil surface and how that residue is distributed on and anchored to the soil, and by affecting the size of soil aggregates and their stability, has a large impact of wind and water erosion. Tillage, through the action of soil disturbance and the downward force of gravity, causes the progressive downslope movement of soil, i.e. tillage erosion. Soil erosion results in the redistribution of soil within fields and losses from fields. Typically, in cultivated topographically complex landscapes soil loss is most severe on hilltops (Fig. 1). Soil loss and accumulation/sedimentation can dramatically change the properties of soil. Resulting changes in soil structure and structural stability affect infiltration, which in turn affects percolation and runoff of water and any contaminants carried by the water. Resulting changes in soil biogeochemical properties (pH, soil nutrient status, soil organic matter content, microbial biomass and activity, etc.) affect pesticide sorption and degradation, production and emission of greenhouse gases, soil biologic abundance, activity and diversity. Consequently, tillage has direct and indirect impacts on water, soil and air quality. Of all farm management practices, tillage may have the greatest impact on the environment.

2.3. Diversity of and changes in tillage

One expects to find a diversity of tillage equipment, practices and systems around the world, reflecting the variety of agroecosystems and the degrees of mechanization and industrialization. However, even within one agroecosystem a wide variety of tillage equipment, practices and systems can exist (Table 1). This variety is the result of socioeconomic and technologic phenomena. For any one crop production system in any one agroecosystem, the selection tillage equipment used by an individual farmer and how it is used may be a function of one or more of: availability, knowledge, technical skills, management skills, stage in one's career, economic pressures, community pressures, and conservation ethic. It must be stated that there is never one perfect tillage system, one that is ideal in terms of agronomics, economics, environment and society. Even within one tillage system, there can be numerous technical options available to farmers. Over time, the phenomena that affect the selection and use of tillage equipment change resulting in an evolution in tillage practices (Tables 2 and 3).

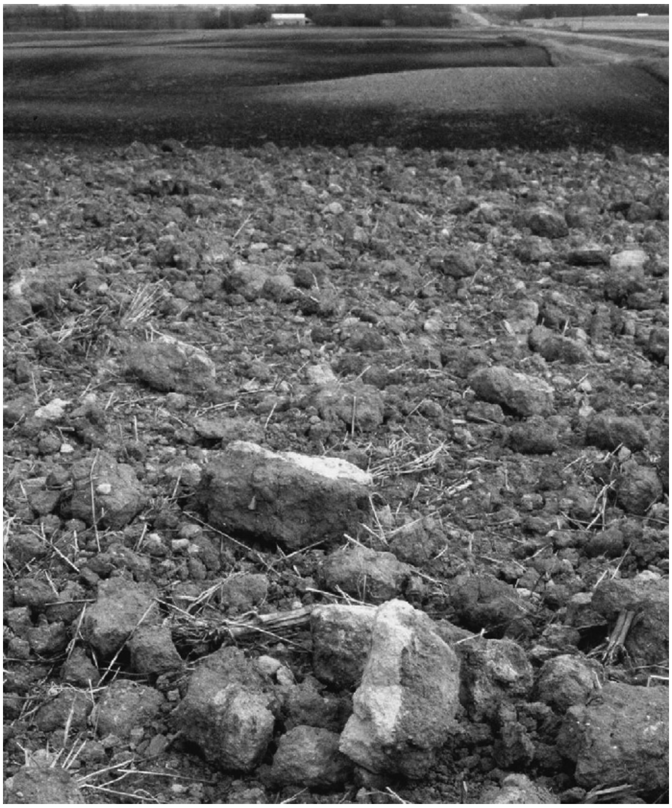

Fig. 1. A landscape in the prairie region that is severely eroded by tillage erosion. In the foreground, note the calcareous subsoil tilled to the surface where it will be incorporated into the surface layer.

The variety associated with tillage practices represents a significant opportunity to enhance environmental performance. This opportunity has made tillage a popular focus of environmental programs and policies. In Canada and United States numerous programs promote reduced tillage. Recent and prominent programs are the Conservation Reserve Program and the Conservation Security Program in the United States and the Permanent Cover Program in Canada.

3. Environmental importance of tillage as a farm management practice

Soil erosion is arguably the most significant cause of environmental degradation by agriculture. Farm management affects soil erosion through cropping and tillage practices. The environmental importance of tillage is demonstrated below by examining models of soil erosion.

3.1. Water erosion

The Universal Soil Loss Equation (USLE), and its derivatives, is widely used to predict average annual soil loss rates by water erosion. Although a simple model, the USLE demonstrates the relative importance of cropping and tillage practices (Table 4). Selection of tillage practices is equally as important as the selection of crops in controlling water erosion. In Table 4 four examples of published data relating the relative impacts of cropping and tillage practices on water erosion. Within annual crop rotations, there is greater impact of changing tillage practices than changing crops in rotation. It is only

Table 1
The diversity of tillage practices in Canada: Tillage statistics for seeded cropland in Canada from the 1996 census of agriculture

Province	Conventional tillage[a]		Conservation tillage[a]		No tillage[a]		Total seeded area	
	(10^3 ha)	(%)[b]	(10^3 ha)	(%)[b]	(10^3 ha)	(%)[b]	(10^3 ha)	(%)[c]
British Columbia	117	65.5	44	24.4	18	10.1	179	0.6
Alberta	4316	56.8	2497	32.9	784	10.3	7597	26.5
Saskatchewan	6089	45.3	4420	32.9	2936	21.8	13,444	46.8
Manitoba	2509	63.3	1090	27.5	362	9.1	3961	13.8
Ontario	1485	59.5	557	22.3	455	18.2	2497	8.7
Quebec	666	80.1	130	15.6	35	4.3	831	2.9
New Brunswick	47	79.5	11	18.4	1	2.1	59	0.2
Nova Scotia	19	77.4	5	19.6	1	3.0	24	0.1
P.E.I.	96	82.0	19	16.3	2	1.8	117	0.4
Newfoundland	1	87.7	<1	8.3	<0.1	4.0	1	<0.1
Canada	15,334	53.4	8772	30.6	4594	16.0	28,709	100.0

Source: Statistics Canada (1997).

[a] Defined in the Census of Agriculture as: Conventional tillage incorporates most of the crop residue into the soil; Conservation tillage retains most of the crop residue on the soil surface; and No tillage prior to seeding.

[b] % of respective area.

[c] % Canada.

Table 2
Changes in tillage practices in Canada: Tillage statistics for seeded cropland from the census of agriculture

Tillage system	1981		1991		1996		2001	
	(10^3 ha)	(%)[a]	(10^3 ha)	(%)[a]	(10^3 ha)	(%)[a]	(10^3 ha)	(%)[a]
Conventional tillage[b]	30,965	100	23,075	68.9	15,334	53.4	12,040	40.5
Conservation tillage[b]	0	0	8182	24.4	8767	30.6	8870	29.8
No tillage[b]	0	0	2251	6.7	4592	16.0	8823	29.7
Total seeded area	30,965	100	33,508	100.0	28,693	100.0	29,733	100.0
Total farm area	65,888		67,754		68,055		67,515	

Source: Statistics Canada (1997, 2003).

[a] % of seeded area in respective census year.

[b] Defined in Table 1.

Table 3
Changes in tillage practices in the United States: Tillage statistics for seeded cropland from the National Crop Residue Management Survey

Tillage system	1990[a]	1992[a]	1994[a]	1996[a]	1998[a]	2000[a]	2002[a]
Intensive Tillage[b]	55.3 48.7%	48.9 42.7%	45.1 39.3%	45.2 38.5%	43.0 36.2%	51.5 42.7%	46.3 40.6%
Reduced Tillage[b]	28.7 25.3%	29.7 25.9%	29.6 25.8%	30.3 25.8%	31.6 26.2%	24.8 20.6%	26.0 22.8%
Conservation Tillage[b]	29.6 26.1%	35.9 31.4%	40.2 35.0%	42.0 35.8%	44.2 37.2%	44.2 36.7%	41.7 36.6%
Ridge-till[c]	1.2 1.1%	1.4 1.2%	1.5 1.3%	1.4 1.2%	1.4 1.2%	1.3 1.1%	1.1 1.0%
Mulch-till[c]	21.6 19.0%	23.2 20.2%	23.0 20.0%	23.3 19.8%	23.4 19.7%	21.7 18.0%	18.2 16.0%
No-till/Strip-till[c]	6.8 6.0%	11.4 9.9%	15.7 13.7%	17.4 14.8%	19.4 16.3%	21.1 17.6%	22.4 19.6%
Total seeded area	113.8	114.5	114.9	117.5	118.8	120.4	113.9

Source: Conservation Tillage Information Centre (2002).

[a] Millions of hectares, and % of total seeded area in respective survey years.

[b] Intensive tillage $<15\%$ residue cover after seeding; Reduced tillage 15–30% cover; Conservation Tillage $>30\%$ cover.

[c] No-till, Strip-till, Ridge-till, and Mulch-till are all considered forms of Conservation Tillage.

possible to have an equal or greater impact with cropping practices if a permanent cover crop, such as hay, is included in the rotation. Much more complex models of water erosion exist (e.g. WEPP: Water Erosion Prediction Program and RUSLE2: Revised Universal Soil Loss Equation). These more complex models, which require much more detailed data on tillage and cropping practices, also demonstrate the similar importance of cropping and tillage practices. Whereas the selection of crops is largely a function of market conditions, the selection of tillage practices is largely a function of technology and, in many instances, can be affected without compromising the economic viability of crop production (PAMI, 2000).

3.2. Tillage erosion

The recognition of tillage erosion is recent; consequently, there are relatively few models of tillage erosion and none with the history or prevalence of the USLE. The most sophisticated of these models was developed by Lobb and Kachanoski (1999). For each tillage operation, erosivity is assessed based on implement type, operating depth and speed. Even more sophisticated models are being developed to include: implement dimensions and tool configuration, available power resulting from the tractor-implement match, tillage pattern, and operator behaviour. Although one could consider tillage to be the only farm management practice involved in tillage erosion, the selection of crops affects the system of tillage equipment and practices used.

4. Use of tillage data in environmental indicators in Canada

Tillage data is a key data requirement for 15 of the current 29 indicators in NAHARP, including indicators for soil cover, wind, water and tillage erosion, soil organic carbon, greenhouse gas emissions, and water contamination by nitrogen, phosphorus, pesticides and pathogens.

Table 4
Sensitivity of water erosion to cropping and tillage practices as indicated by C-Factor values from the universal soil loss equation for water erosion

Crop sequence/Rotation	Tillage system				
	Conventional		Conservation		No-Till
	Fall	Spring	Fall	Spring	
Soybeans grown continuously[a]		**0.49**		0.33	**0.29**
Corn grown continuously[a]		0.37		0.31	0.29
Corn, soybean[a]		0.43		0.32	0.29
Corn, corn, soybean[a]		0.40		0.31	0.29
Corn, corn, soybean, small grain, meadow[a]		0.20		0.18	0.14
Corn, soybean, small grain, meadow[a]		0.16		0.15	0.11
Corn, corn, small grain, meadow[a]		**0.12**		0.13	0.09
Soybeans grown continuously[b]	**0.48**	0.41	0.36	0.29	**0.20**
Corn grown continuously[b]	0.36	0.29	0.17	0.14	0.06
Corn, soybean[b]	0.41	0.35	0.22	0.18	0.12
Corn, corn, soybean[b]	0.39	0.33	0.20	0.16	0.10
Corn, corn, soybean, small grain[b]	0.32	0.36	0.15	0.12	0.06
Corn, soybean, small grain[b]	0.30	0.25	0.14	0.11	0.06
Corn, soybean, meadow[b]	0.19	0.15	0.10	0.08	0.03
Corn, soybean, small grain, meadow[b]	**0.17**	0.13	0.09	0.07	0.04
Corn grown continuously[c]	**0.40**	0.36		0.27	**0.10**
Corn, soybeans[c]	0.42	0.37		0.24	0.12
Corn, oats, meadow[c]	0.072	0.065		0.042	0.040
Corn, corn, oats meadow[c]	0.13	0.12		0.10	0.064
Corn, oats, oats, meadow[c]	**0.055**	0.050		0.033	0.033
Corn, soybean[d]	**0.53**			0.22	**0.06**
Corn, soybean, wheat, meadow[d]	0.20			0.13	0.05
Corn, oats, hay, hay[d]		**0.05**			0.03

[a] C Factor values for northern Illinois. Source: Brady (1984).
[b] C Factor values for central Illinois. Source: Siemens et al. (1993).
[c] C Factor values for Ohio. Source: Miller and Gardner (2001).
[d] C Factor values for midwestern United States. Source: Brady and Weil (1999).

Two of these indicators are described below to demonstrate the use and importance of tillage data.

4.1. Soil cover indicator

Crop residues are widely recognized as a key factor in the environmental performance of crop production systems. The interest in crop residues has been primarily due to their ability to reduce soil erosion by water and wind. Crop residues absorb the impact of raindrops and slow water movement over the soil surface. In doings so, they protect the surface structure and porosity of the soil, retain the soil's infiltration capacity and increase the infiltration of rainfall, thereby reducing the amount of runoff as well as its rate. Consequently, the erosive forces of rainsplash and runoff are diminished. Crop residues also protect the soil from the erosive force of wind. The reduction of soil erosion by wind and water results in a reduction in the movement within and in the loss from the field of nutrients, pesticides and other potential contaminants associated with soil particles. Crop residues, when left in the field, build up soil organic matter which enhances a variety of soil properties, including the erodiblity of soil to wind and water. Leaving crop residues on the soil surface reduces the exchange of energy, water and greenhouse gases with the atmosphere. Crop residues also serve as food and shelter for wildlife.

The Soil Cover Indicator provides an estimate of the number of days in a year that a unit of cropland would be expected to have soil cover (Soil Cover Days, SCD) or to lack soil cover (Bare Soil Days, BSD, equal to 365 minus SCD). Given the benefits of soil cover, farming practices designed to provide greater soil cover, such as using forage rotations, planting cover crops, reducing tillage frequency and intensity, and eliminating straw burning and harvesting, are considered beneficial management practices. In most cases, adoption of practices that increase soil cover constitutes more sustainable agriculture. The performance objective for this indicator is to move the level of cover from "very low" levels ($<$249 SCD/yr) to "very high" levels ($>$325 SCD/yr).

This indicator takes account of soil cover by crop canopy, crop residue and snow, and is based on a unique value for each crop under each of three tillage systems (conventional, conservation and no tillage, as defined in Table 1). The value calculated for a spatial unit (Soil Landscapes of Canada (SLC) polygon, ecodistrict, Province, etc.) is the area-weighted average for all crops and tillage practices within that unit, as reported by the Census of Agriculture. Preparation of the fundamental data on the number of days with bare soil for each region, crop and tillage combination is based on the development, using field data and regional expertise, of a wide range of BSD tables. In estimating the number of bare soil days, a number of factors are accounted for:

- the day of the year on which significant changes in soil cover occur (planting, harvesting, tillage) and the magnitude of those changes,
- canopy development between planting and full canopy,
- the decomposition and loss of residue over the winter, and
- the total number of days of snow cover.

The amount of time (elapsed time) associated with each proportion of soil cover is then calculated and summed to give the total number of days of bare soil for the year. For example, 2 days of 50% cover for 1 unit of land results in 1 BSD for that unit, while similarly 1 unit of hay with 100% cover for 1 day plus one unit of summerfallow with 0% cover for 1 day results in 0.5 BSD. The annual values for each crop/tillage combination are area-weighted by the land area under that combination to give an average for a land unit. Soil cover is calculated on the basis of field conditions over a single 'typical' year, although, conceptually, it could be calculated for any time frame, depending on data availability. The soil cover indicator is reported every 5 years to coincide with the Census of Agriculture.

The BSD tables were developed from field data collected to determine C (cropping) Factor values for the USLE at a number of sites across the Canada in the 1980s. This data collection involved actual field residue measurements made using the 'knotted rope' method at strategic times during the year under a variety of crop and tillage combinations. Tillage practices and timing of field operations information was added from farmer interviews and records and field survey. These tables were extrapolated to similar crop/tillage combinations in other ecoregions within an ecozone, checked against extension bulletins and verified in some cases by extension specialists and field staff. Finally, a canopy-growth function was incorporated into the table in order to account for soil cover development over the growing season, a 5% over-winter residue decomposition factor was incorporated, and the average number of days of snow cover for the appropriate ecodistrict was extracted from Agriculture and Agri-Food Canada's (AAFC) climate normals database (1971–2000) and subtracted from the total number of days of bare soil for each table.

In total, there are 608 BSD tables currently available, covering 85% of the cropland in the country. Those based on field data cover 55% of national cropland, verified extrapolations cover an additional 10%, and the remaining 20% are covered by unverified extrapolations. However, even using these tables, the 85% is a national figure and a number of crops and practices of regional importance are missing. Given the importance of these tables, the primary data gap is a reliable, uniform and substantiated suite of tables for all crops, tillage practices and regions. This would require verification of the current tables for currentness and accuracy, considering new tillage implements and crop varieties, extrapolation and verification of existing tables to additional areas and development of new tables for a number of crops with regional importance, such as berries, orchards, grapes and sugar beets. Based on the fundamental principles on which the ecostratification hierarchy was developed (the ecological composition of landforms, soils, water, and vegetation) and the number of polygons at each level of stratification, the indicator is built on unique BSD tables for each crop/tillage combination in each ecoregion. The ecoregion BSD values are used for each SLC polygon within the ecoregion. SCD for selected crops and tillage systems within two agroecosystems are shown in Table 5.

4.2. Tillage erosion risk indicator

Tillage erosion is caused by the progressive downslope movement of soil by tillage (Govers et al., 1999). Tillage erosion is a distinct process from wind and water erosion. NAHARP includes indicators for wind, water and tillage erosion (Van Vliet et al., 2003), and an integrated soil erosion indicator has been proposed (Lobb et al., 2003).

The model that underlies the tillage erosion indicator (Lobb, 1997) is simple, but informative. Tillage erosion is a function of the erodibility of a landscape and the erosivity of the tillage system used on that landscape. Hilly landscapes with steep slopes are highly erodible; for

Table 5
Soil Cover Days for selected crops and tillage systems within two agroecosystems

Ecoregion	Province	Crop	Tillage system[a]	Soil cover days
156	Manitoba	Spring wheat	Conventional	302
			Conservation	327
			No tillage	338
156	Manitoba	Canola	Conventional	267
			Conservation	275
			No tillage	283
135	Ontario	Barley	Conventional	209
			Conservation	254
			No tillage	266
135	Ontario	Corn	Conventional	234
			Conservation	270
			No tillage	308
135	Ontario	Soybean	Conventional	188
			Conservation	224
			No tillage	264
135	Ontario	Winter wheat	Conventional	200
			Conservation	219
			No tillage	257

[a] Tillage systems defined in Table 1.

example, intensely hummocky landscapes. Crops that are frequently tilled with implements that are sensitive, in terms of soil movement, to changes in slope steepness are highly erosive; for example, conventionally tilled potato production. The following equation is used to calculate tillage erosion rates:

$$A_{\mathrm{TE}} = E_{\mathrm{T}}\, E_{\mathrm{L}},$$

where A_{TE} is the rate of soil loss (or accumulation) by tillage erosion ($\mathrm{t\,ha^{-1}\,yr^{-1}}$); E_{T} the tillage erosivity ($\mathrm{t\,\%^{-1}\,m^{-1}\,yr^{-1}}$); E_{L} the landscape erodibility ($\mathrm{\%\,m\,ha^{-1}}$).

Tillage erosivity is ascertained for each SLC polygon from the cropping and tillage practices reported in the Census of Agriculture database. E_{T} values are assigned to each combination of crop and tillage system based on tillage erosion research. Existing E_{T} values (Table 6) are based on the research of Lobb et al. (1995, 1999).

Landscape erodibility is ascertained for each SLC polygon from the surface form class and slope class of the National Soil Data Base. Each SLC polygon is represented by modal surface form, which is described in terms of slope gradient and slope length, of the dominant and subdominant units. E_{L} is calculated for selected combinations of surface form class and slope class. Class combinations used for the tillage erosion indicator are those used for the water erosion indicator. Landscape erodibility is calculated using the following equation:

$$E_{\mathrm{L}} = 10000\, S\, L^{-1}\, p^{-1},$$

where S is the slope gradient assigned to each SLC polygon (%); L is the slope length assigned to each SLC polygon (m); and p is the proportion of L that is convex and, therefore, on which soil is lost (soil accumulation occurs on the portion of the slope length that is concave).

Tillage erosion rates are calculated for individual SLC polygons and can be aggregated to ecodistricts, ecoregions and ecozones, provinces, regions or the nation. SLC polygons are the smallest spatial units within the National Ecological Framework for Canada, in which SLC polygons are nested within ecodistrict polygons which are nested within ecoregion polygons which are nested within ecozone polygons (McRae et al., 2000).

Using the soil erosion indicators, as of 1996, it was estimated that approximately 50% of the cropland in Canada was subjected to unsustainable levels of tillage erosion (Table 7). In comparison, using the water erosion risk indicator it was estimated that only approximately 15% of the cropland was subjected to unsustainable levels of water erosion (Table 8), and using the wind erosion risk indicator only approximately 30% was subjected to unsustainable levels of wind erosion (Padbury and Stushnoff, 2000). These values represent the proportions of the number cropped land units (area-weighted). Typically, for a given unit of cropland, tillage erosion causes significant soil loss on approximately 20–30% of the area (hilltops), water erosion causes significant soil loss on approximately 30–50% of the area (backslopes of hills), and wind erosion causes significant soil loss on approximately 20–50% of the area (Lobb et al., 2003). Although there has been a dramatic reduction in the intensity of tillage systems since 1981, tillage erosion remains a serious concern across Canada. The tillage erosion indicator is critical to a comprehensive assessment of soil erosion, of the impact that land use and management change has on soil erosion, and of the impacts that policies and programs have on soil erosion via land use and management change (Lobb et al., 2003).

Table 6
Tillage erosivity values for crop and crop groups for southern Ontario

Crop or crop group	Conventional tillage operations[a]	Tillage erosivity ($\mathrm{kg\,m^{-1}\,\%^{-1}}$)		
		Conventional tillage	Conservation tillage[b]	No tillage[c]
Spring-sown cereals	P-S-S	5.0	2.5	0.0
Corn for grain	P-S-S	5.0	2.5	0.0
Canola, peas, beans, soybeans, buckwheat	P-S-S	5.0	2.5	0.0
Potatoes	P-S-S-R-R-H	7.0	3.5	NA
Corn for silage	P-S-S	5.0	2.5	0.0
Fall-sown cereals	P-S-S	5.0	2.5	0.0
Hay (alfalfa)*	(P-S-S)/3	1.70	0.80	0.0
Fallow	P-S-S-S	6.0	3.0	NA
Nursery Crops	NA	0.0	0.0	0.0
Vegetables	P-S-S-R-H	6.0	3.0	0.0
Tree fruits, grapes	NA	0.0	0.0	0.0
Small fruits	NA	0.0	0.0	0.0
Tobacco	P-S-S-R	6.0	3.0	0.0
Grass hay, pasture[d]	(P-S-S)/3	1.70	0.80	0.0
Sod (turf grass)	P-S-S-S	6.00	3.00	0.0

[a] P = primary tillage; S = secondary tillage; R = row cultivation; H = root crop harvesting.
[b] Assumed that Conservation Tillage has one-half the tillage intensity of Conventional Tillage.
[c] Assumed that soil disturbance and there for tillage erosion is negligible.
[d] Assumed that tillage is required to establish forage and pasture in first year of three years growth.

Table 7
Risk of tillage erosion on Canadian cropland[a] in 1981 and 1996

Province[b]	Cropland[c] (10^6 ha)	Proportion of cropland (%) in various risk classes									
		Tolerable[d]		Low[d]		Moderate[d]		High[d]		Severe[d]	
		1981	1996	1981	1996	1981	1996	1981	1996	1981	1996
British Columbia	0.5	30	50	42	36	28	14	<1	0	0	0
Alberta	10.6	47	62	24	19	26	19	3	0	0	0
Saskatchewan	18.8	29	35	14	19	52	46	5	0	0	0
Manitoba	4.9	22	44	53	38	24	18	1	0	0	0
Ontario	3.4	33	41	21	35	43	24	3	<1	0	0
Quebec	1.6	68	75	21	16	11	9	0	0	0	0
New Brunswick	0.1	33	38	26	32	32	21	3	8	6	1
Nova Scotia	0.1	40	66	52	28	8	6	0	0	0	0
P.E.I.	0.1	50	50	29	30	10	10	11	10	0	0
Canada	40.1	35	46	23	23	38	31	4	<1	<1	0

[a] Includes seeded and summer fallow (tilled, but not seeded).

[b] Tolerable (sustainable) $<6\,\mathrm{t\,ha^{-1}\,yr^{-1}}$; Low $= 6$–$11\,\mathrm{t\,ha^{-1}\,yr^{-1}}$; Moderate $= 11$–$22\,\mathrm{t\,ha^{-1}\,yr^{-1}}$; High $= 22$–$33\,\mathrm{t\,ha^{-1}\,yr^{-1}}$; Severe $>33\,\mathrm{t\,ha^{-1}\,yr^{-1}}$.

[c] Newfoundland excluded based on the small area of cropland.

[d] Average values for 1981 and 1996. Source: King et al. (2000).

Table 8
Risk of water erosion on Canadian cropland[a] in 1981 and 1996

Province[b]	Cropland[c] (10^6 ha)	Proportion of cropland (%) in various risk classes									
		Tolerable[d]		Low[d]		Moderate[d]		High[d]		Severe[d]	
		1981	1996	1981	1996	1981	1996	1981	1996	1981	1996
British Columbia	0.5	56	56	25	19	12	19	5	5	2	1
Alberta	10.6	75	83	15	11	8	6	2	1	<1	<1
Saskatchewan	18.8	64	90	24	5	7	5	4	1	2	<1
Manitoba	4.9	88	89	5	4	3	4	1	1	3	2
Ontario	3.4	51	58	26	27	13	6	10	10	<1	<1
Quebec	1.6	89	88	7	9	4	3	0	0	0	0
New Brunswick	0.1	43	48	23	30	22	14	6	5	6	3
Nova Scotia	0.1	74	72	14	15	10	10	<1	<1	2	2
P.E.I.	0.1	59	59	23	23	14	19	4	0	<1	0
Canada	40.1	70	84	19	9	7	5	3	2	1	<1

[a,b,c,d] See notes for Table 7. *Source*: Shelton et al. (2000).

5. Methods of collecting data on tillage practices in Canada

Data on tillage practices can be collected through surveys of farmers, surveys of local/regional experts, monitoring field operations, and sales of equipment. The challenge in collecting such data for the purpose of long-term, national initiatives is ensuring accuracy and consistency for a whole country over many decades, and doing so using limited funding. For such purposes, census surveys are often the most practical means of collecting data on tillage practices and other farm management practices.

5.1. Census of agriculture

Most countries carry out a census of agriculture. In Canada, this census is carried out by Statistics Canada, a department of the federal government. It takes place every 5 years, the most recent in 2001. All individuals who report income from agricultural activities are required to complete the Census of Agriculture survey. Data is collected at the farm scale and reported for Census Reporting Areas that correspond to geopolitical boundaries such as parishes and townships.

Data on crop production has been collected since the first Census of Agriculture. Data on tillage practices were first collected in 1991. The survey questions pertaining to crops and tillage are:

> "Areas of selected field crops, tree fruits or nuts, berries or grapes, vegetables, nursery products or sod, Christmas trees."
>
> "What is the area of land prepared or being prepared for seeding in 1991 using:

- *conventional tillage* which incorporates most of the crop residue (trash) into the soil.

- *conservation tillage* which retains most of the crop residue (trash) on the surface (include minimum tillage practices).
- *no tillage* prior to seeding (include direct seeding into stubble or sod, and ridge tillage).''

There are a few problems with census of agriculture surveys that bear some discussion: continuity of the census data, spatial allocation of census data, and interpretation of census survey questions.

5.2. Enhancing data on tillage practices for use in environmental indicators

Due to the large number of survey questions in the Census of Agriculture, very little direction is provided to respondents — it is not feasible to provide any explanatory information. Consequently, there are always some data of poor quality. Questions on tillage practices and soil and water conservation practices have been problematic. The most problematic is the question regarding the use of ''no tillage''. Farmers, the agricultural industry at large and the provincial governments do not use the term ''no tillage'', they use ''No-Till'', ''Zero-Till'' or ''direct seeding''. Although No-Till is the most widely used term, in the prairie region, which accounts for the majority of the country's cropped land, farmers use the term Zero-Till in reference to seeding into soil which has not been tilled. Some farmers prefer to use the term direct seeding and not associate their practices to either No-Till or Zero-Till systems. In such cases, the farmer may direct seed only some of the crops in rotation and till to prepare for the seeding of other crops — ''rotational tillage''. As a consequence of a lack of understanding of terminology and a lack of explanation in the census, in 1991 some areas of the Atlantic region were reported by the federal government as having significant amounts of No-Till crop production when there was in fact none; farmers were simply not tilling some of their lands and leaving them fallow. The terms definitions ''conventional'' and ''conservation'' are also subject to interpretation. There exists a wide range of tillage practices in use at the farm level, and there may be discrepancies in the manner in which these practices are reported by producers. For example, would a producer report a normal fall tillage pass that was missed due to poor weather as 'conservation tillage'? Would an 'additional-to-normal' tillage pass for weed control using a conservation implement constitute conventional or conservation tillage? Furthermore, the use of relative terms such as ''incorporates most of the crop residue into the soil'' or ''leaves most of the crop residue on the surface of the soil'' makes the interpretation of census data challenging; some crops produce residues which cover 90% of the soil surface while others only 10%. In contrast, in the United States whether a tillage system is conventional or conservation is based on the level of crop residue left of the soil surface following seeding; more than 30 % cover constitutes conservation tillage and less than 30% constitutes conventional tillage.

Statistics Canada tests the census survey questions to ensure the highest possible degree of comprehensibility and accuracy. The consequence is very simple, very general, and sometimes qualitative questions, as illustrated above. The accuracy of the responses is assessed by Statistics Canada and adjustments are made to the data to improve the quality of the data. However, the magnitude of errors and the nature of such adjustments are treated as confidential information by Statistics Canada.

Data that is absolute such as percent residue coverage following seeding would be much easier to use for modelling and indicators, but it would demand much greater knowledge and skills on the part of the farmer. Ideally, what would be most useful is a measure of tillage intensity that incorporates soil mixing, residue incorporation and soil movement (Fig. 2).

A major limitation with agricultural census data is the fact that data is collected once in every 5 years. Such infrequent surveying makes it very difficult to capture the variability and changes in farm management practices.

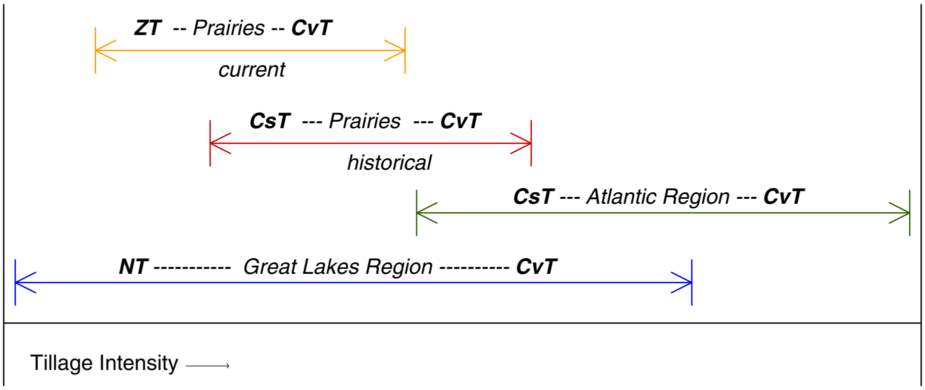

Fig. 2. Illustration of the relative intensity of tillage systems for agroecosystems across Canada and over time in the Prairies (ZT = Zero-Till; NT = No-Till; CsT = Conservation Tillage; CvT = Conventional Tillage).

One of the primary weak points in current applications of tillage data from the Census of Agriculture is that the Census asks each producer, and thus reports simply the total crop area under each of conventional, conservation and no tillage practices. In the absence of a feasible method to do otherwise, the proportional representation of these practices is applied identically to all crops in the SLC polygon. For example, if the Census results for a particular area show that 40% of cropland is under conventional tillage, 40% is under conservation tillage and 20% is under no-till, we assume that 40% of each crop in the area is under conventional tillage, etc. This is not necessarily the case, as some crops, soil types and crop rotations are more or less amenable to different tillage practices.

Several activities are underway to enhance the available data on crop and tillage practices for NAHARP and other initiatives. A major project has been initiated to explore the potential for, and to develop crop-specific allocation routines. The hypothesis is that by working with individual farm records, a matrix of crops and tillage distributions can be created that will allow a more structured allocation of tillage distributions. For example, compiling a routine that uses the tillage distribution of all farms with only one crop versus the tillage distribution of all farms with two crops versus the tillage distribution of all farms with three crops may lead to a rigorous methodology for allocating different tillage distributions to different crops. Such an allocation routine will significantly improve the accuracy of all applications of census tillage data. As part of the ongoing indicator enhancement efforts are being made to collect detailed, accurate data on tillage practices to enhance the interpretation of census data.

6. Conclusions

Information on tillage practices is important in the modeling of environmental processes and in the use of environmental indicators. There are several actions that could be taken by agencies to enhance these modeling and indicator initiatives:

- Data on tillage practices should be collected as part of the information gathered on farm management practices for the uses of environmental indicators. Of all farm management practices, tillage may have the greatest impact on the environment. Differences and changes in tillage practices must be captured to accurately reflect trends in environmental impacts and to affect these trends through policy and programs.
- To ensure differences and changes in tillage practices are meaningful, it is necessary to have explicit definitions of tillage equipment, practices and systems. The use of terms relating to tillage, and their meaning, will always vary between countries and within regions of countries, and over time; therefore, these terms should be defined in sufficient detail to make accurate comparisons.
- Qualitative terms such as "conventional tillage" are highly problematic; a more quantitative approach should be considered. With detailed data on tillage, it is possible to use terminology based on quantitative measures of tillage intensity.
- Data collected on tillage practices should have sufficient detail to satisfy models of biophysical processes such as soil erosion.
- Measures should be taken to ensure the accuracy of the tillage data collected through surveys and census. In addition to using accepted methods of verification, these measures should include greater education of those providing data and those collecting data.
- More focus in environmental policies and programs should be given to tillage practices. A wide variety of tillage equipment, practices and systems are available to farmers, providing opportunities to enhance environmental performance.

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