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Agricultural Impacts on Soil Erosion and Soil Biodiversity: Developing Indicators for Policy Analysis

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SOIL EROSION PROCESSES AND THEIR INTERACTIONS: IMPLICATIONS FOR ENVIRONMENTAL INDICATORS

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Abstract

Historically, scientists and policy makers have dealt with wind and water erosion as independent biophysical processes. With the recent recognition and understanding of tillage erosion has come a new appreciation of the complexity of soil erosion processes in that they are interrelated, not independent. The removal of soil by one erosion process can affect the erodibility of the remaining soil to other erosion processes, and one soil erosion process can act as a delivery mechanism for other erosion processes by depositing soil where it is more readily removed by those other erosion processes. The issue of interactions between biophysical processes extends beyond soil erosion. Soil erosion also impacts other processes such as water contamination with sediments and nutrients, pesticide fate in the soil and the environment, and greenhouse gas production and emission. This presentation examines the interactions between soil erosion processes and between soil erosion. The discussion focuses on the implications for the development and implementation of environmental indicators for agriculture. Although interactions can complicate modelling efforts, there is a tremendous opportunity to increase the accuracy, coherency and efficiency of environmental indicator initiatives. This point is demonstrated using the agri-environmental indicators being developed and enhanced by Canada.

Introduction

Historically, scientists have dealt with soil erosion processes independently. This approach has been taken for a number of reasons. Within any given region, one erosion process usually predominates over the others and, thus, becomes the sole focus of research. Each erosion process is highly complex; consequently, the demands of research limit activities to one erosion process and its impacts. Water erosion, for example, requires a thorough understanding of: water movement by splash, sheet and concentrated flow; particle detachment, entrainment, transport and sedimentation by water; and the temporal and spatial variability of controlling factors. As well, to achieve expert status and, thereby, success, scientists must specialize. Policy makers have taken a similar narrow approach to soil erosion processes. This is a reflection of the science and the information it generates, and the need to generalize and simplify. With the recognition of tillage erosion as a geomorphic process has come a new appreciation of the complexity of soil erosion processes, in that they are interrelated, not independent, and an interest in a new approach to this science and its application in policy.

Tillage erosion: the overlooked geomorphic process

Only recently, has tillage erosion been recognized by the scientific community, with several studies conducted around the world in the past decade (Govers *et al.* 1999).

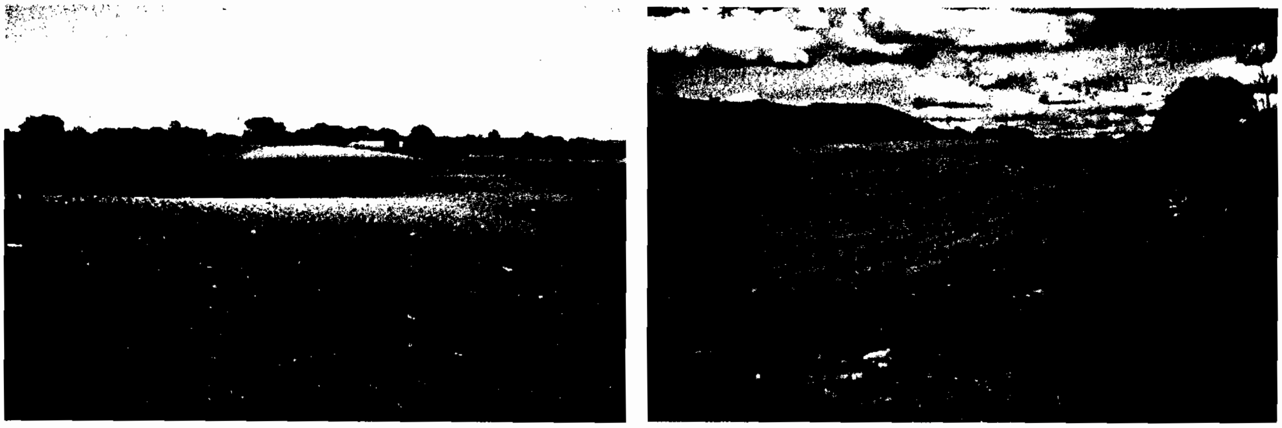
Keywords: Soil erosion, Tillage erosion, Process interaction, Process scaling, Model integration, Environmental Indicators

Tillage erosion is the loss and accumulation of soil within a landscape resulting from the net movement of soil caused by the variability of tillage translocation, the resultant displacement of soil by tillage. The magnitude and variability of tillage translocation, and therefore tillage erosion, are affected by the design and operation of tillage implements and by the topographic and soil properties of landscapes. Typically, tillage erosion results in the progressive downslope movement of soil, causing soil loss on upper slope landscape positions (convex) and accumulation on lower slope positions (concave) - tillage erosion is most severe in landscapes that are intensively tilled and topographically complex. In such landscapes, tillage erosion is responsible for the majority of the severe soil loss observed on upper slopes and is responsible for a significant amount of the gross (wind, water and tillage erosion combined) soil redistribution within the landscape (Lobb *et al.* 1999).

Significance of tillage erosion in Canada

Using the tillage translocation data of Lobb *et al.* (1995, 1999), the Tillage Erosion Risk Indicator (TERI) model (Lobb, 1997), 1996 agriculture census data, and landscape data from the National Soil Data Base, King *et al.* (2000) concluded that approximately 50 % of the cropland in Canada was subjected to unsustainable levels of tillage erosion (Table 1). A similar assessment was made for water erosion by Shelton *et al.* (2000) using water erosion risk indicator, and it was found that only approximately 16 % of the cropland was at risk of unsustainable levels of water erosion (Table 2). Within any given piece of cropland, water erosion results in soil losses from 40 to 60 % of the area (back and foot slopes) and tillage erosion results in soil losses from 20 to 40 % (shoulder slopes and crests). A similar assessment was made for wind erosion by Padbury and Stushnoff (2000) using the wind erosion risk indicator, and it was found that only 30 % of the cropland was at risk of unsustainable levels of wind erosion. Tables 1 and 2 indicate that the risk of water erosion and the risk of tillage erosion have decreased between 1981 and 1996, as has the risk of wind erosion. This decrease is due to the adoption of conservation tillage practices (Table 3). The analyses by King *et al.* (2000), Shelton *et al.* (2000) and Padbury and Stushnoff (2000) were based on the assumption that the area in conservation tillage in 1981 was negligible. Soil degradation by erosion in Canada remains widespread (Figure 1) with intensive tillage practices being used on approximately 50 % of the cropland.

Figure 1. Hilly landscapes typically show signs of severe soil erosion.
a) Deep glacial tills of the prairie region with calcareous subsoil exposed on hilltops.
b) Shallow glacial tills of the Appalachian region with exposed bedrock on hilltops



Recognition of the interaction between erosion processes

Although some scientists have stated that the interaction between wind and water erosion is minimal (Toy *et al.* 2000), this interaction has not been researched. Lobb (1991) identified the interaction between tillage erosion and wind and water erosion. Soil loss by tillage erosion exposes subsoil which is often more highly erodible to the erosive forces of wind and water. Tillage erosion acts as a delivery mechanism for water erosion, transporting soil to areas of concentrated overland water flow, *i.e.* rills and convergent landforms. This delivery process has also been noted by Lobb *et al.* (1995), Govers *et al.* (1996), Lobb and Kachanoski (1999), Quine *et al.* (1994, 1999) and Schumacher *et al.* (1999). Recognition of the potential significance of the interaction of soil erosion processes has raised questions regarding the integration of erosion models and the scaling of their outputs.

Table 1. Risk of tillage erosion on Canadian cropland[1] in 1981 and 1996 (King *et al.* 2000)

Province [3]	Cropland [4] (10^6 ha)	Proportion of cropland (%) in various risk classes									
		Tolerable [2]		Low [2]		Moderate [2]		High [2]		Severe [2]	
		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

1: includes seeded and summer fallow (tilled but not seeded).

2: Tolerable (sustainable) < 6 t ha^{-1} yr^{-1}; Low = 6-11 t ha^{-1} yr^{-1}; Moderate = 11-22 t ha^{-1} yr^{-1}; High = 22-33 t ha^{-1} yr^{-1}; Severe > 33 t ha^{-1} yr^{-1}

3: Newfoundland excluded based on the small area of cropland.

4: average values for 1981 and 1996.

Table 2. Risk of water erosion on Canadian cropland[1] in 1981 and 1996 (Shelton *et al.* 2000)

Province [3]	Cropland [4] (10^6 ha)	Proportion of cropland (%) in various risk classes									
		Tolerable [2]		Low [2]		Moderate [2]		High [2]		Severe [2]	
		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

1, 2, 3 and 4: see notes for Table 1

Table 3. Tillage statistics for seeded cropland in Canada from the 1996 census of agriculture

Province	Conventional tillage		Reduced tillage [3]		No tillage		Total seeded area	
	(10^3 ha)	(%) [1]	(10^3 ha)	(%) [1]	(10^3 ha)	(%) [1]	(10^3 ha)	(%) [2]
British Columbia	117	65.5	44	24.4	18	10.1	179	0.6
Alberta	4,316	56.8	2,497	32.9	784	10.3	7,597	26.5
Saskatchewan	6,089	45.3	4,420	32.9	2,936	21.8	13,444	46.8
Manitoba	2,509	63.3	1,090	27.5	362	9.1	3,961	13.8
Ontario	1,485	59.5	557	22.3	455	18.2	2,497	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	15,343	53.4	8,772	30.6	4,594	16.0	28,709	100.0

1: % of respective area; 2: % Canada; 3: retaining most of residue on surface.

Source: Statistics Canada 1997.

Objective

The objectives of this presentation are: to examine the interactions between soil erosion processes; and, to examine the implications for the development and use of environmental indicators for soil erosion and other related biophysical process. Canada's approach to process interaction, processes scaling and model integration in developing agri-environmental indicators is presented.

Interactions between soil erosion processes

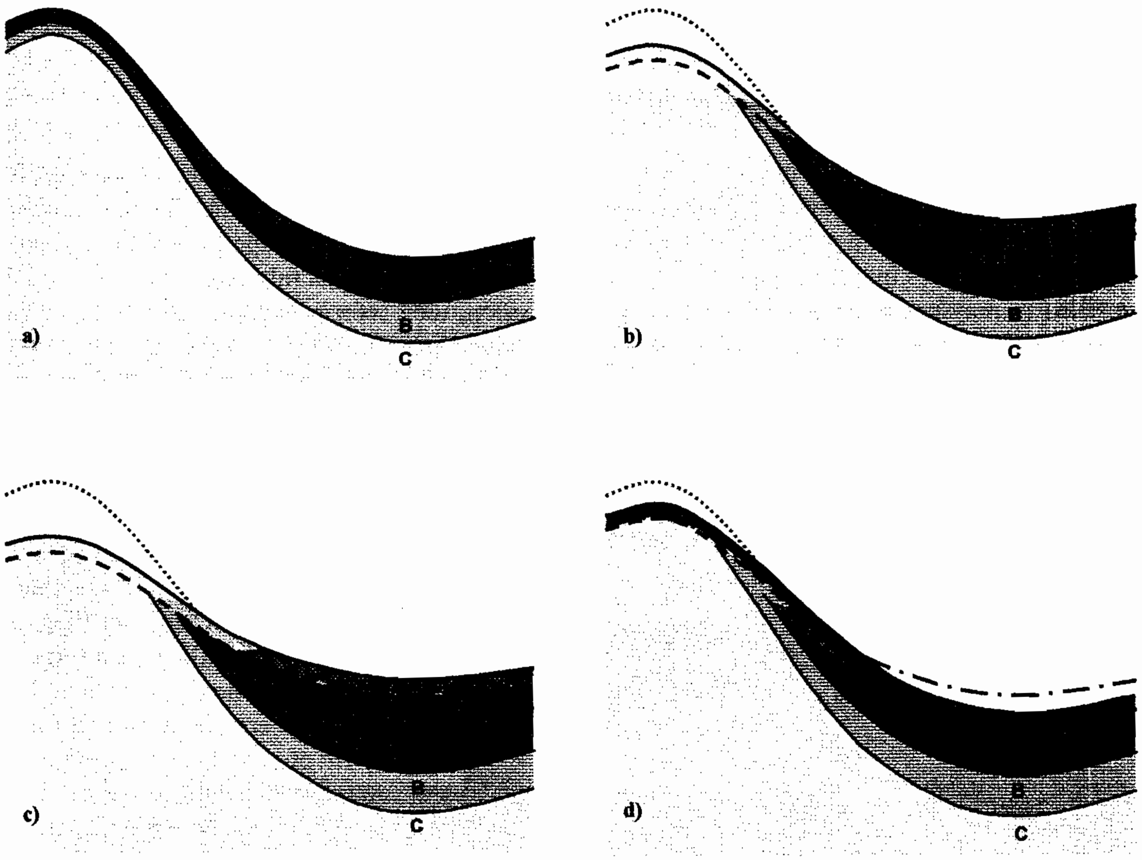
One process increases the erodibility to another

The loss of soil by any erosion process affects the erodibility of the soil to wind and water erosion. Typically, soil loss increases the erodibility of the soil. Within the soil profile the uppermost layer is subject to the most intense biological activity resulting in higher organic matter content, more stable structure and greater permeability than underlying soil. These conditions make the surface soil less erodible to wind and water erosion than the subsurface material. Wind and water erosion remove soil from the surface and progressively act on deeper and more erodible material. If tillage takes place, as soil is lost tillage will cut deeper into the subsoil and mix more erodible material into surface layer (Figure 2). Although not common, situations can exist where the subsurface material is less erodible than the surface material due to inherent textural or structural variations with depth, or the presence of shallow bedrock or frozen subsoil (Figure 1b). To appreciate the impact of one soil erosion process on another, consider the impact of tillage erosion on the erodibility of soil to water erosion. A hypothetical cultivated, topographically complex landscape in the prairie region of Canada is used for illustration (Figure 3), and the USLE K-Factor is used to indicate soil erodibility. Prior to and including the first cultivation (about the year 1900 in the selected region), soil properties over the landscape's surface are near-uniform and, therefore, the K-Factor is near-uniform. Given uniform soil erodibility, and assuming uniform rainfall erosivity and vegetative cover, water erosion is solely a function of topography. Soil loss increases down slope to a maximum on the lower backslope and decreases further down slope; ultimately, deposition of sediment occurs at the base of the slope or sediment is carried from the landscape. This is the characteristic spatial pattern or signature for water erosion. With continued cultivation and soil loss, assuming water erosion is the only form of erosion on this landscape, more erodible subsoil is incorporated into the surface soil, and the resulting change in erodibility over the surface amplifies the spatial pattern of water erosion.

Figure 2. A landscape in the prairie region that is severely eroded by tillage erosion.
On the hilltop in the foreground, note the calcareous subsoil tilled to the surface where it will be incorporated into the surface layer

With cultivation, tillage erosion also acts on the landscape, removing soil from the crest and shoulder slope positions exposing highly erodible subsoil. Based on the observed patterns of soil loss within the landscapes of the prairie region, the maximum rates of soil loss by tillage erosion (on a landscape position basis) are presumed to be equal to or greater than those of water erosion. The change in soil erodibility over a landscape caused by tillage erosion must affect the spatial pattern of water erosion; the quantities of runoff and soil loss from the upper slope positions will increase.

[redacted] The progressive impact of soil erosion on the redistribution of soil within a topographically complex prairie landscape (adapted from Ellis 1938). a) uncultivated state, circa 1900; b) mature state of erosion, circa 1996; c) advanced state of erosion; and d) restored landscape. Dotted line indicates original surface. Dashed lined indicates till-layer. Dashed-dotted line in d indicates surface before restoration



To quantify the potential change in erodibility for the variety of soil types that could be found on such a landscape, ranges of soil organic matter, soil structure and permeability were established for surface soil and subsoil. This data was used to calculate K-Factor values for the surface soil and the subsoil, assuming that the subsoil values represent the surface soil in a severely eroded state (data not shown). The change in K-Factor values was found to be between 300 % and 1000 %. For a clay loam soil, which is typical of the hilly, glacial till landscapes of the prairie region, the change was estimated to be about 600 %. The fact that the effect of a 3-fold increase in soil erodibility on soil loss is equivalent to the effect of a 9-fold increase in slope length (USLE L-Factor) demonstrates the significance of soil erodibility in the variability and dynamics of soil erosion within a landscape.

The effect of tillage erosion on wind erosion may be greater than that on water erosion in hilly landscapes. Tillage erosion removes soil from and exposes highly erodible subsoil on upper slope landscape positions where the erosive force of wind is greatest (Figure 2).

Although tillage erosion clearly increases the severity and extent of wind and water erosion, soil loss by wind or water erosion does not have a clear effect on tillage erosion. The variability in tillage translocation is affected directly and indirectly by soil properties. Soil bulk density will affect the mass of soil moved for a given tillage depth; soil bulk density, moisture content and structure will affect the power required to draw an implement through the soil and, therefore, will affect the variability in tillage depth and speed; and soil moisture content and structure will also affect the nature of soil movement during tillage (Lobb *et al.* 1999). By affecting the variability of soil properties within a landscape, wind and water erosion have the potential to affect tillage erosion.

As well, it should be noted that sediments deposited by wind and water on the soil surface are typically more erodible than the materials that they bury, which may increase the loss of soil by some future wind and water erosion events. Sediments are destructured and depleted of clays and organic matter. This is not the case for tillage erosion. Soil that is redistributed by tillage does so through bulk transport rather than particle transport.

One process a delivery mechanism for another

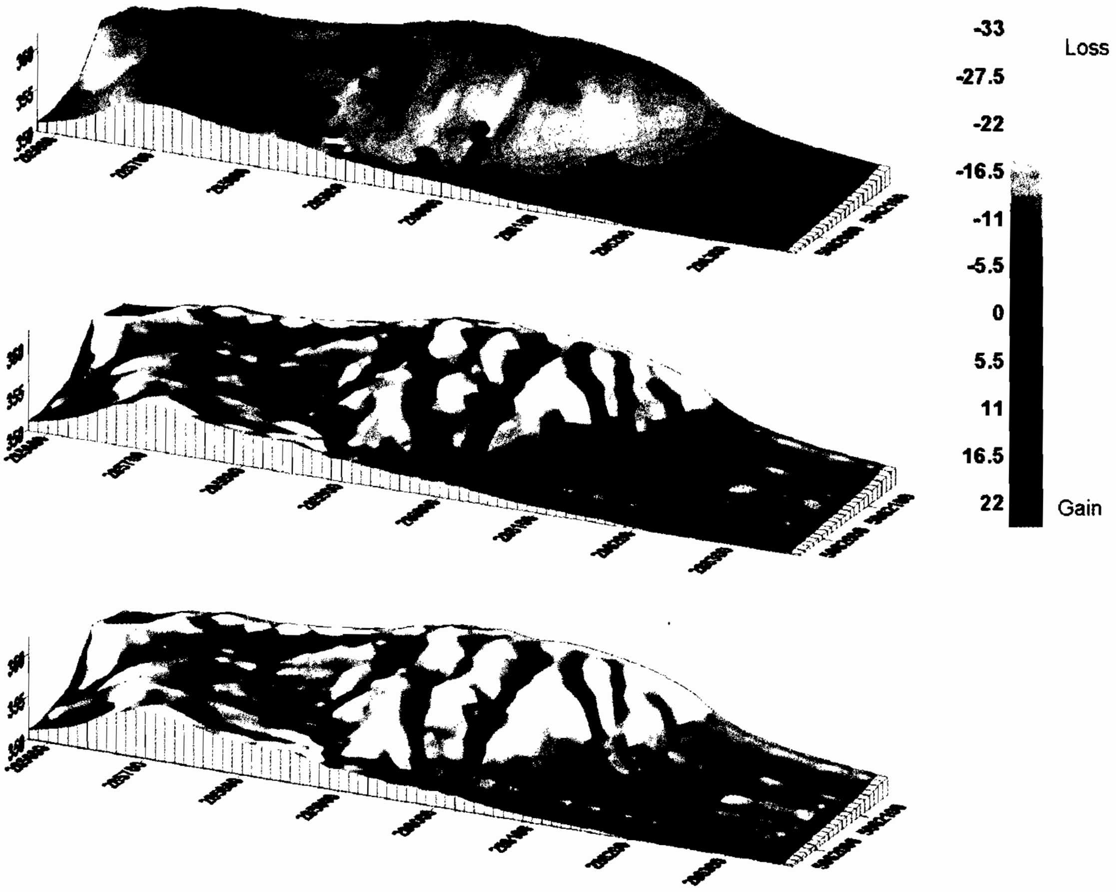
One soil erosion process can act as a delivery mechanism for another; more specifically, any erosion process can act as a delivery mechanism for water erosion. The channels formed by water erosion (rills and gullies) are sinks for soil moving over the landscape by any erosion process. Soil that moves into these channels is flushed out by water erosion (although channels which are filled in may not reform in exactly the same location, they reform in same general location, where water converges). Normally, in the study of water erosion, inter-rill erosion (splash and sheet flow) is considered the only mechanism for delivery of soil to these channels. This may be true during water erosion events, but this narrow view of erosion neglects the fact that wind and tillage erosion can deliver considerable amounts of soil between water erosion events. The accumulation of soil by tillage erosion occurs in convergent landforms where these channels form. As well, the infilling of rills and gullies by tillage is a form of tillage erosion. The delivery of soil to rills by tillage erosion must equal that lost by rill erosion (assuming negligible delivery by wind erosion). This fact is implicit in the operation of all major water erosion models, such as USLE, RUSLE, WEPP, as they assume that the rills from one water erosion event, or sequence of events, are eliminated by tillage before the next. Typically, rill erosion is greater in magnitude than inter-rill erosion; therefore, it may be concluded that tillage erosion is more significant than inter-rill erosion as a delivery mechanism for rill erosion. Bulldozers or graders, rather than tillage implements, are often required to infill gullies, but the action of such large machinery is a form of tillage. Although tillage erosion is likely to be more significant as a delivery mechanism for water erosion than wind erosion, it still may be significant in some situations (Figure 4).

Figure 4. Sediment from wind erosion infilling a rill caused by water erosion

Attribution of soil losses within a landscape

Although one or two erosion processes may dominate a landscape due to climate and topographic conditions, all will occur to some degree in cultivated landscapes. The soil loss that results from each will not be uniform. This is particularly true for water and tillage erosion, which are strongly controlled by topography (Figure 5). Soil loss by water erosion increases down slope as slope length and gradient increase to a maximum on the lower backslope and decreases further down slope as slope gradient decreases; ultimately, deposition of sediment occurs at the base of the slope or sediment is carried from the landscape. Across the slope, soil losses are obviously greatest within the rills and/or gullies, but losses across the slope are represented as averages due to the fact that these channels are regularly eliminated by tillage. Soil loss by tillage erosion occurs on convex slopes and soil accumulation occurs on concave slopes, and both are a function of the change in slope gradient – uniform soil losses occur where curvature is uniform, maximum losses occur where the degree of curvature is greatest. As stated above, within a cultivated landscape water erosion results in significant soil losses from 40 to 60 % of the landscape (back and foot slopes) and tillage erosion results in significant soil losses from 20 to 30 % (shoulder slopes and crests).

Figure 5. Soil erosion by a) water and b) tillage, and c) the sum of water and tillage erosion predicted using WaTEM (Van Oost *et al.*, 2000). Water erosion predicted using R = 90, K = 0.29, C = 0.45, P = 1. Tillage erosion predicted using one pass of moldboard plough and two passes of tandem disk. Soil erosion expressed as a loss in t ha^{-1} yr^{-1}



It is interesting to note that within most cultivated landscapes evidence of long-term tillage erosion is often highly visible and evidence of long-term water erosion is not (Figures 1 and 2). The reason for this is simple: tillage erosion delivers soil to the landscape positions where water erosion soil losses occur, obscuring the evidence of water erosion, and the contribution of tillage erosion to gross soil redistribution is relatively large. Typically, soil loss by tillage erosion occurs over smaller areas within landscapes than water erosion, but at much higher rates. Studies by Lobb and Kachanoski (1999) and others elsewhere in the world have shown that the contribution of tillage erosion to gross soil redistribution within cultivated, topographically complex landscapes can be equal to or greater than wind and water erosion, and when this is the case, the delivery of soil by tillage erosion will offset losses by water erosion.

Implications for indicators of soil erosion

Clearly, soil erosion processes interact and must be accounted for. Acceptance of these facts has significant implications for how research on soil erosion is conducted, how erosion processes are represented in models, and how erosion processes are controlled through practices and policies.

A new generation of soil erosion models

The assessment of soil erosion within a landscape cannot be limited to one erosion process. Although wind, water and tillage erosion may not be of equal importance in any one landscape, they must all be assessed, individually and in aggregate. The fact that erosion processes do not operate uniformly within landscapes requires these assessments to be spatially explicit. The interactions between soil erosion processes can be significant and, therefore, cannot be neglected. The interaction between erosion processes has never been explicitly accounted for in the development and validation of erosion models. Consequently, much of the soil erosion attributed to one process may be largely in part due to that of another erosion process. Case in point, tillage erosion may be largely responsible for the erosion attributed to water erosion due to is impact on soil erodibility and its role as a delivery mechanism. To account for the interactions between soil erosion processes in modelling, an integrated approach must be taken. The sustainability of land management systems must be assessed based on gross soil erosion using comprehensive and integrated erosion models. Ideal indicators are those built on process-based models. Compared to empirical models, process-based models are more transferable in space and time, and are more easily integrated with models of other processes. To achieve the above requires a new generation of soil erosion models, which requires new research to develop such models. It is recognized that indicators rely on input data sets that are usually inadequate for complex process-based models, and, as a consequence, indicators use simplified models. However, confidence can only be placed in such indicators when the simple models are developed from and tested against the more accurate complex process-based models.

The Canadian approach

In Canada there are environmental indicators for wind, water and tillage erosion. These indicators were developed as part of the Agri-Environmental Indicators Project (1993-2000) and are described in a companion paper (van Vliet *et al.* 2003). Output from the water and tillage erosion indicators is presented in Tables 1 and 2. These erosion indicators use common input data and are operated in tandem; however, they are independent. The indicator of tillage erosion risk is spatially explicit (assessed on and reported for only that portion of the landscape which is convex – crest and shoulder slope landscape positions). The indicators of water and wind erosion risk are not spatially explicit (the portion of the landscape subjected to wind and water erosion is not assessed), and, as a consequence, it is often incorrectly assumed that the reported soil losses apply to entire landscapes.

An initiative is underway as part of the National Agriculture Health Assessment and Reporting Program (2002-2008) to enhance existing indicators of wind, water and tillage erosion and to develop an integrated indicator for soil erosion. Several erosion models are being reviewed to determine if there are models for wind, water and tillage erosion which use common input data, generate comparable quantitative output data, and are spatially explicit. If there are, it will be possible to develop an integrated soil erosion indicator, one in which models for all three erosion process are operated in tandem. However, to do so several actions must be taken: 1) The existing landform classification system must be enhanced by making it more descriptive by adding landform elements (landscape positions) and by validating it through the use of digital terrain analyses on the wealth of digital elevation data that exists across Canada. 2) The landform data in the National Soil Data Base must be revised to reflect the enhanced landform classification system. Currently, the database includes landform type, slope gradient and slope length, but the application of landform type classification varies somewhat between provinces, the definition of slope•gradient varies amongst the numerous soil surveys that were conducted across the country over several decades, and the application of the definition of slope length varies considerable between the provinces. 3) The relationship between landscape position and soil loss/accumulation must be established for each soil erosion process. Some knowledge of these relationships does exist, but a systematic study should be carried out to provide confidence in the attribution of soil loss within landscapes. 4) A comprehensive budget approach for the redistribution of soil amongst landscape positions must be developed. This is necessary to account for the fact that soil losses by tillage erosion offset soil losses by water erosion within a landscape. 5) Gross soil erosion estimates from the integrated erosion model must be validated. This can be done using the spatial signatures for wind, water and tillage erosion, using model optimization techniques, and using radioisotope techniques (^{137}Cs and ^{210}Pb) which can provide estimates of gross soil erosion. 6) Limits of sustainable soil loss for gross erosion must be established. Currently, a sustainable limit of 6 t ha^{-1} yr^{-1} is applied to each erosion process and applied uniformly across the country. This is wholly inadequate and greatly diminishes the credibility of the indicators of soil erosion. It is essential that sustainable limits of gross soil loss be developed based soil loss-crop productivity relationships, and that these relationships be developed and applied over the range of landscape and climate conditions that exist in Canada. Although this initiative does not include research to develop more complex process-based erosion models that account for the interaction between soil erosion processes, this work is being undertaken as part of complementary initiatives.

If it is not possible to identify models for wind, water and tillage erosion which use common input data, generate comparable quantitative output data, and are spatially explicit, and, therefore, it is not possible to carryout the initiative as described above, a risk classification scheme will be developed to report on the combined risk of wind, water and tillage erosion. As is currently done, each indicator will have five qualitative risk classes ranging from negligible to severe; however, each class will be assigned a quantitative value ranging from 1 to 5, respectively. Ratings would be summed for a landscape, and a landscape with a combined risk rating of 3 would be at no risk of soil erosion and a landscape with a combined risk rating of 15 would be at high risk to all three types of soil erosion. It would not be possible from the combined risk rating to determine the specific causes, controls or impacts of the soil erosion. Furthermore, it would not be possible to determine whether the soil losses from the three forms of soil erosion are occurring from the same portion of the landscape or from different portions of the landscape. It would not account for the possibility that one form of erosion may mask another. By carrying out some of the actions of the initiative described above, it would be possible to assign the soil loss from each erosion process to positions within the landscape, and the risk ratings could be weighted based on the aerial extent of landscape positions.

Summary

The interactions between soil erosion processes are significant and bear further consideration and research. This new area of research will require innovative experimental techniques as well as a broader approach to the study of soil erosion. Although it is not possible at this time to use models that account for the interactions between soil erosion process, it is possible to make a major step in that direction by integrating models of wind, water and tillage erosion. The increasing application of erosion models in the form of environmental indicators demands greater defensibility and, therefore, greater accuracy and coherency. As well, there is a strong demand to generalize environmental indicators, for example, a soil quality index, or even more general, an environmental quality index. Integration of soil erosion models is necessary to meet these demands. The work initiated in Canada represents a significant move in this direction.

Recommendations for consideration by OECD

- A comprehensive approach must be taken in developing and using indicators of soil erosion; that is, there must be indicators for wind, water and tillage erosion.

- An integrated approach must be taken in developing and using indicators of soil erosion. The models for wind, water and tillage erosion must be consistent in terms of inputs and outputs, providing more comparable and, therefore, more meaningful assessment of soil erosion, its controls and its impacts. Consistency will also allow the assessment of gross soil erosion.

- These indicators of wind, water and tillage erosion must be spatially explicit at the landscape-scale. Spatially explicit models allow the integration of outputs at the landscape-scale necessary for the assessment of gross soil erosion. This is also the mechanism for scaling up the results from soil erosion models and indicators.

- Further soil erosion research must be encouraged, and this research must be focused on the interactions between soil erosion processes. Although not available today, the results from this research are needed to develop the more accurate erosion models and indicators of the future that account for the interactions between soil erosion processes.

- An integrated approach must be taken in developing environmental indicators in general. Environmental indicators for greenhouse gas emissions, pesticide fate, surface water contamination, etc. which are affected by soil erosion, must incorporate soil erosion models and these models must be the same models used in the soil erosion indicators (Lobb *et al.* 2003)

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