THE RELATIONSHIP BETWEEN LANDSCAPE POSITION, TILLAGE PRACTICES, AND SOIL LOSS: MODEL DEVELOPMENT

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Prepared for: Centre for Land and Biological Resources Research
Agriculture Canada

Submitted to: Dr. A. Hamill, Research Scientist
Agriculture Canada Research Station
Harrow, ON N0R 1G0

September, 1993

FINAL REPORT

EXECUTIVE SUMMARY

In 1987 the University of Guelph initiated a soil erosion study, *Management of Farm Field Variability II. Soil Erosion Processes on Shoulder Slope Landscape Positions* (SWEEP/TED), at two field sites in southwestern Ontario, one in Brant County and the second in Middlesex County. The study measured tillage translocation and tillage erosion on convex upper slope landscape positions. The estimated rate of soil loss resulting from net downslope translocation was in excess of 6.5 kg m^{-2} yr^{-1} at the Brant Co. field site and in excess of 4.5 kg m^{-2} yr^{-1} at the Middlesex Co. field site. Subsequent examination of that data recognized that tillage erosion was responsible for at least 70 % of the total soil lost on the upper slope landscape positions based on estimates of total soil loss using resident ^{137}Cs.

A second study, *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* (SWEEP/TED), by the University of Guelph from 1990 to 1991 at two field sites in Huron County was conducted to determine the effect of tillage implement type on the magnitude of tillage translocation and tillage erosion under a range of slope gradients in topographically complex landscapes. All four tillage implements, the chisel plough, mouldboard plough, tandem disc and field cultivator, were found to be erosive, causing soil loss on upper slope landscape positions and soil accumulation in lower slope landscape positions.

Tillage erosivity, the potential for tillage events to erode soil within a landscape, was recognized to be a function of several physical and human parameters, including: tillage tool shape and arrangement within a tillage implement, tillage implement length and width, tractor-implement match, tillage depth and tillage ground speed, and tillage operator response to varying landscape conditions. The tillage parameters are controlled by selection and varied by the operator. Landscape erodibility, the potential for the soil within the landscape to be eroded by tillage events, was recognized to be a function of the topographic and soil parameters, including: slope gradient and curvature, and field soil bulk density, soil moisture content, and the ability of the soil to resist displacement and translocation (internal friction due to cohesion and adhesion). The landscape parameters evolve through erosion.

The objective of this, the third study conducted by the University of Guelph, was to define the relationship between tillage erosion and landscape position in the form of a model based on the data collected in the Huron County study.

In the proposed model, tillage erosion was calculated as the net translocation at specified points in the landscape, the difference between the soil translocated into a point and the soil translocated out from that point during a single tillage operation. Tillage translocation was related to slope gradient and slope curvature by a simple linear function. The translocation in to and out from a point was calculated from forward and backward differences in topographic conditions. Therefore, the model predicted soil redistribution from forward tillage translocation along two-dimensional landscape profiles.

The proposed tillage erosion model was calibrated using experimental data from the Huron Co. study *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* (SWEEP/TED).

The proposed tillage erosion model was validated using data collected during two preceding studies, *Management of Farm Field Variability I. Quantification of Soil Loss in Complex Topography* (SWEEP/TED) conducted in Brant County and *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* (SWEEP/TED) conducted in Huron County. Resident ^{137}Cs radioactivity was used to estimate soil redistribution within the landscapes of the field sites. These estimates of soil loss and accumulation were compared to those predicted by the tillage erosion model based on the topography of the field sites.

The proposed tillage erosion model provided a reasonably accurate prediction of soil redistribution at the Brant County field site when compared to that estimated using resident ^{137}Cs radioactivity. The tillage erosion model provided a relatively poor prediction of soil redistribution at the Huron County field site when compared to that estimated using resident ^{137}Cs radioactivity. There is some indication that the poor prediction for the Huron site was due in part to the model's simplicity (not able to predict the effect of curvature asymmetry on tillage erosion - a problem which would be greater at this site than the Brant site because of smaller scale of the ridge). Soil losses, based on the ^{137}Cs data, were situated on the convex upper slope landscape positions, but they were greater in severity on the shoulder slope position of the steeper of the ridge's two slope faces. Although the model correctly predicted the general pattern of soil losses and accumulations, the model underpredicted the magnitude, or severity, of soil losses at both field sites. Too few data of soil accumulation estimates were available to make a similar inference about soil accumulation. Several possible reasons for this underprediction of soil loss were identified: 1) the tillage implements and the tillage sequence used to predict the soil redistribution may have been less intensive than those responsible; 2) inaccuracies associated with the use of resident ^{137}Cs may have caused overestimation of soil redistribution (the problem associated with point measurements resulting in apparent losses on backslope positions, as well, the current level resident ^{137}Cs for a noneroded site may be much less than the assumed 2500 Bq m^{-2} in Huron County); 3) wind and water erosion may have caused soil redistribution in addition to that caused by tillage erosion (the redistribution pattern is inconsistent with that of soil erosion by overland water flow).

For a first attempt at modelling tillage erosion in complex landscapes the performance of the proposed model was considered very good. Clearly, there are limitations to the complexity and consequently predictive capabilities of the model due to the lack of experimental data for calibration procedures, particularly tillage depths. At the time the study was initiated the number of parameters involved and the complexity of the relationships was not fully appreciated. This was exploratory research, and therefore presuming that a model could be developed on such a data set was very ambitious.

The fact that the proposed tillage erosion model predicts greater rates of soil loss on convex upper slope landscape positions where severe soil loss occurs, and soil accumulation in concave lower slope landscape positions where soil accumulation is observed, indicates that this model is more appropriate than water erosion models for predicting soil erosion in topographically complex landscapes. Consequently, it can be presumed that the proposed tillage erosion model is more appropriate than water erosion models for basing soil conservation decisions relating to soil degradation and soil productivity. Comprehensive soil erosion models including submodels for erosion by wind, water and tillage may provide the best prediction of soil redistribution in topographically complex landscapes.

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INTRODUCTION

Sound farm management requires the ability to identify and predict areas of soil loss and accumulation. The basis of this ability lies in the understanding of the soil erosion processes responsible for the degradation of soil, and either directly or indirectly responsible for the contamination of surface waters. The culmination of this understanding is the development of models which can accurately predict the magnitude of soil redistribution within landscapes. The identification of existing or potential soil erosion problems allows the farm manager to target conservation efforts, maximizing the efficiency and profitability of the farm operation.

In 1987 the University of Guelph initiated a soil erosion study at two field sites in southwestern Ontario, one in Brant County and the second in Middlesex County. The study reported in Lobb (1990) and Lobb et al. (1992a) measured tillage translocation and tillage erosion on convex upper slope landscape positions. The estimated rate of soil loss resulting from net downslope translocation was in excess of 6.5 kg m^{-2} yr^{-1} at the Brant Co. field site and in excess of 4.5 kg m^{-2} yr^{-1} at the Middlesex Co. field site. Subsequent examination of that data (Lobb, 1993) recognized that tillage erosion was responsible for at least 70 % of the total soil lost on the upper slope landscape positions based on estimates of total soil loss using resident ^{137}Cs.

A second study by the University of Guelph from 1990 to 1991 at two field sites in Huron County reported in Lobb et al. (1992b) was conducted to determine the effect of tillage implement type on the magnitude of tillage translocation and tillage erosion under a range of slope gradients in topographically complex landscapes. All four tillage implements, the chisel plough, mouldboard plough, tandem disc and field cultivator, were found to be erosive, causing soil loss on upper slope landscape positions and soil accumulation in lower slope landscape positions.

The objective of this, the third study conducted by the University of Guelph, study was to define the relationship between tillage erosion and landscape position in the form of a model based on the data collected in the Huron County study.

PROPOSED MODEL DESIGN

In the proposed model, tillage erosion was calculated as the net translocation at specified points in the landscape, the difference between the soil translocated into a point and the soil translocated out from that point during a single tillage operation. Positive net translocation indicated the loss of soil mass and negative net translocation indicated the accumulation of soil mass. The translocation in to and out from a point was calculated from forward and backward differences in topographic conditions. In this form, the model predicted soil redistribution from forward tillage translocation along two-dimensional landscape profiles.

Tillage translocation, T (kg m^{-1}), was related to slope gradient, è (%), and slope curvature, ö (% m^{-1}), in the following linear function:

$$T = á + â è + ã ö ,$$

where á (kg m^{-1}) is the translocation by tillage unaffected by slope gradient or slope curvature, that which would occur on level surface; â (kg m^{-1} %$^{-1}$) and ã (kg m^{-1} %$^{-1}$ m) are coefficients to describe the additional translocation resulting from slope gradient and slope curvature, respectively.

The following function has also been developed to describe the process of tillage translocation:

$$T = M_t ë = M_t (ë_á + ë_â + ë_ã) = ñ_t D_t (ë_á + ë_â + ë_ã),$$

where M_t is the specific soil mass of the till layer (kg m^{-2}); $ñ_t$ is the soil bulk density (kg m^{-3}); D_t is the tillage depth (m); ë is the translocation distance (m); $ë_á$ is the translocated distance unaffected by slope gradient or slope curvature (m); $ë_â$ is the additional translocated distance resulting from slope gradient (m); and $ë_ã$ is the additional translocated distance resulting from slope curvature (m), the `scalping' and `filling' due to pulling a fixed frame over a curved surface.

In its nonlinear form the function is:

$$T = ñ_t D_t (ë_á + â_ë è^b + ã_ë ö^c),$$

where $â_ë$ (m %$^{-1}$) and $ã_ë$ (m %$^{-1}$ m) are coefficients to describe the additional translocated distance resulting from slope gradient and slope curvature, respectively; and b and c are coefficients to describe the nonlinearity.

The translocation distance, ë, is a length parameter which is equal to the proportionality constant, ô in the response function for the instantaneous impulse applied to the soil by the tillage tools:

$$T = M_t (1/ô e^{x/ô}),$$

and in the response function for the continuous impulse applied to the soil by the tillage tools:

$$T = \rho_t D_t (1-e^{-x/\tau}) = \rho_t D_t (e^{-x/\tau}).$$

both of which can be used to describe the process of translocation. The response function for the continuous impulse, as a model for tillage translocation, predicts the magnitude of translocation as well as the extent of displacement, i.e. the `mixing length'.

Tillage depth and tillage speed vary considerably in complex landscapes, as was indicated by Lobb et al. (1992b). Tillage depth, tillage speed and soil bulk density determine the draught requirements on the tractor. The varying force of gravity on the tractor and tillage implement as they move through complex topography causes the potential power output necessary to meet the draught requirements to change, therefore the tillage operator changes either tillage depth or gear ratio (and consequently tillage speed), or both, in response. Variations in tillage depth greatly affect the magnitude of translocation because tillage depth determines the specific mass of the till layer. Variations in tillage depth and tillage speed also affect the translocation distance.

A simple function to describe tillage depth, D, in complex topography is:

$$D = D_\alpha + D_\beta + D_\gamma.$$

In its nonlinear form the function is:

$$D = D_\alpha + \beta_D \theta^e + \gamma_D \phi^f,$$

where e and f are coefficients to describe the nonlinearity.

A simple function to describe tillage speed, S, in complex topography is:

$$S = S_\alpha + S_\beta + S_\gamma.$$

In its nonlinear form the function is:

$$S = S_\alpha + \beta_S \theta^g + \gamma_S \phi^h,$$

where g and h are coefficients to describe the nonlinearity.

The relationship between tillage depth and tillage speed may be as simple as:

$$D = k_D S,$$

for a constant field bulk density, where k_D is a constant.

The inclusion of parameters to describe the effects of tillage speed and tillage depth on translocation distance would clearly result in a more comprehensive, and probably more accurate, model. In the experimental data set used to calibrate the proposed tillage erosion model, tillage speed measurements for the primary tillage operations were not instrumented, and even when they were instrumented for the secondary tillage treatments the precision was somewhat less than adequate. Tillage depth was measured by hand for the primary tillage treatments and for the secondary tillage treatments could not be measured for secondary tillage treatments.

Given the limitations of the data set to be used for calibration, the proposed model was reduced to the prediction of tillage translocation simply as a function of slope gradient and curvature. The proposed model related tillage translocation for different tillage implements to slope gradient and curvature. Tillage depth and tillage speed are required to more accurately represent the tillage process, but tillage depths measurements were not available for the secondary tillage implements, therefore it was impossible to relate either tillage depth or tillage speed to tillage translocation. Tillage depth and tillage speed were assumed to be inherent in the relationship between translocation and slope gradient and curvature.

Consequently, the proposed model for tillage translocation as a function of slope gradient and slope curvature was:

$$\mathbf{T = á + â è + ã ö .}$$

The proposed model for tillage erosion (net translocation, T_N) as a function of slope gradient and slope curvature was:

$$\mathbf{T_N = (á + â è_O + ã ö_O) - (á + â è_I + ã ö_I).}$$

where $è_O$, $ö_O$, $è_I$ and $ö_I$ are forward (output) and backward (input) differences, respectively. Clearly, tillage erosion, T_N, is a function of slope curvature as defined by the forward and backward difference in slope gradient, but tillage translocation, T, is also a function of slope curvature due to the `scalping' and `filling' caused by pulling a fixed frame over a curved surface.

MODEL CALIBRATION

The proposed tillage erosion model was calibrated using experimental data from the study *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* (Lobb et al., 1992b). The objective of this study was to examine tillage translocation by four different implements under the variable soil and topographic conditions of natural landscapes. Since the objective was to examine tillage translocation under natural field conditions the tillage operator varied tillage depth and tillage speed in response to the changing landscape conditions. The four tillage implements examined were chisel plough, mouldboard plough, tandem disc, and field cultivator. The tillage translocation for each tillage implement was related to slope gradient, slope curvature, tillage depth, and tillage speed.

Tillage translocation was quantified using chloride as a tracer. The experimental method whereby tracers are used to quantify tillage translocation is described in Lobb (1990) and Lobb et al. (1992a). Translocated soil volume was calculated at each plot relative to the 25 cm depth of the labelled plots. Translocated soil mass was then calculated using the average soil bulk density for each plot's landscape position.

Primary tillage treatments, mouldboard plough and chisel plough, were conducted in the summer of 1990 on a farm field site owned by Mervin Lobb in Goderich Twp., Huron County. A single large asymmetric ridge cut across the width of the experimental area. Carbonates observed on the soil surface of the ridge summit indicated that severe soil loss had occurred on the upper slope landscape positions of the experimental area. There were very few stones in the sandy loam soil, but fine gravel tongues were observed in the subsoil at the crest of the ridge. The treatments traversed this ridge running parallel with the direction of tillage and cropping, and to the adjacent fencerow.

Secondary tillage treatments, tandem disc and field cultivator, were conducted in the summer of 1991 on a farm field owned by Gordon Lobb also in Goderich Twp, Huron County. A single large asymmetric ridge cut across the width of the experimental area. A smaller second ridge was situated at the far end of the treatments. Carbonates observed on the soil surface of the ridge summit indicated that severe soil loss had occurred on the upper slope landscape positions of the experimental area. There were very few stones in the sandy loam soil. The treatments traversed this ridge running parallel with the direction of tillage and cropping. Prior to the establishment of the secondary tillage treatments, the tandem disc treatments were tilled with the mouldboard plough, and the field cultivator treatments were conducted with the mouldboard plough and the tandem disc.

A subset of the soil samples collected at each plot for tracer analysis were also analyzed for ^{137}Cs radioactivity. Resident ^{137}Cs was used to generate soil erosion estimates for validation of the model.

Several factors which can affect the magnitude of tillage translocation were identified, including: slope gradient, slope curvature, tillage depth, tillage speed, the response of the tillage operator, the efficiency of the tillage implement-tractor match, and the position of the tractor relative to the tillage implement - the `leading effect'. The relationships between some of these parameters were examined, but few relationships were statistically significant. The data set was characterized as extremely variable. In addition to experimental error, unexplained variability resulted from the inability to accurately quantify many of these parameters. Even though there was extreme variability, some trends were observed. To more clearly define the relationships much more extensive experimentation would have been necessary and was beyond the limits of funding in this study.

In theory, translocation for each tillage implement was expected to increase as slope gradient (downslope), slope curvature (convexity), tillage depth, tillage speed were increased. In a supplementary experiment described by Lobb et al. (1992b), tillage speed was not found to have a significant effect on tillage translocation by the mouldboard plough indicating that the form of the relationships may be specific to tillage implement.

For this study, it was assumed that simply examining the relationship between translocated soil mass and slope gradient and curvature would also include the effects of tillage depth and tillage speed, since they are related to topography. Therefore, this data set was considered adequate for the development of the tillage erosion model, at least to derive first approximations for the basic relationship between translocation and topography. The problem in determining the separate effects of slope gradient and slope curvature on tillage translocation is that slope curvature is typically greatest at low slope gradients, therefore, translocation at low gradients was confounded by curvature and translocation at low curvatures was confounded by gradient. Slope curvature is most easily examined in exclusion of slope gradient on the crest slope position or the base of the slope where the slope gradient is zero. Slope gradient is most easily examined in exclusion of slope curvature on landscapes where there is no curvature - uniform backslope positions.

Prior to calibration, the data was reexamined to provide more detailed topographic information, specifically slope curvature. When the complete data sets of the four tillage implements were reexamined for relationships between the mass of soil translocated, T, and slope gradient, è, slope curvature, ö, tillage speed, S, and tillage depth, D. Few relationships indicated statistical significance. This information was not used for the calibration, however, it served to assess the limitations for using the whole data set for developing a tillage erosion model.

The plots presumed to be most affected by slope gradient were selected to determine the relationship between translocation and slope gradient. The plots presumed to be most affected by slope curvature were selected to determine the relationship between translocation and slope curvature. This selection excluded many plots where the data was most variable, presumably where the interactions between tillage translocation and slope gradient, slope curvature, tillage depth and tillage speed were more complex and more difficult to explain. More exhaustive complex analysis may have provided better definition of the relationships between parameters, but without measurements of such a critical parameter as tillage depth, it was not considered. Instrumentation to monitor tillage depth was not available at the time of the experiments. Such instruments are now available commercially.

Slope Gradient

To determine the relationship between tillage translocation and slope gradient only those plots where slope gradient was relatively large in comparison to slope curvature were selected for calibration. This selection was conducted by examining the ratio between slope gradient, è, and slope curvature, ö. Plots 3, 4 and 8 at the M. Lobb field site and plots 2, 3, 7 and 8 at the G. Lobb field site were selected for calibration. Calibration consisted of simple linear regression analysis. The basic form of the equations used to describe the relationship between tillage translocation and slope gradient is:

$$\mathbf{T = \text{á} + \text{â}\ \text{è}}$$

where T is translocated mass of soil (kg m^{-1}), á is the y intercept (kg m^{-1}), â is the slope of the regression (kg m^{-1} %$^{-1}$), and è is the slope gradient (%).

The relationship between the mass of soil translocated by the chisel plough and slope gradient for plots 3, 4, and 8 selected for calibration was:

$$\mathbf{T_{CP} = 25.50 + 0.430\ \text{è}, \quad (r^2 = 0.503)}$$

(see Figure 1), and for plots 4 and 8, which were the most uniform in slope gradient relative to curvature, was:

$$\mathbf{T_{CP} = 27.24 + 0.376\ \text{è}, \quad (r^2 = 0.530)}.$$

The relationship between the mass of soil translocated by the mouldboard plough and slope gradient for plots 3, 4, and 8 selected for calibration was:

$$\mathbf{T_{MP} = 34.61 + 0.955\ \text{è}, \quad (r^2 = 0.866)}$$

(see Figure 2), and for plots 4 and 8, which were the most uniform in slope gradient relative to curvature, was:

$$\mathbf{T_{MP} = 35.79 + 0.894\ \text{è}, \quad (r^2 = 0.938)}.$$

The relationship between the mass of soil translocated by the tandem disc and slope gradient for plots 2, 3, 7 and 8 selected for calibration was:

$$\mathbf{T_{TD} = 24.78 + 0.987\ \text{è}, \quad (r^2 = 0.926)}$$

(see Figure 3), and for plots 7 and 8, which were the most uniform in slope gradient relative to curvature, was:

$$\mathbf{T_{TD} = 23.34 + 1.059\ \text{è}, \quad (r^2 = 0.974)}.$$

The relationship between the mass of soil translocated by the field cultivator and slope gradient for plots 2, 3, 7 and 8 selected for calibration was:

$$\mathbf{T_{FC} = 29.84 + 0.313\ \text{è}, \quad (r^2 = 0.215)}$$

(see Figure 4), and for plots 7 and 8, which were the most uniform in slope gradient relative to curvature, was:

T_{FC} = 31.65 + 0.265 è,   (r^2 = 0.713).

To test the appropriateness of such a simple linear model the relationship between the residuals from the predicted translocation for slope gradient, slope curvature, tillage speed and tillage depth were examined. There were no evident relationships that would suggest that the simple linear models were inappropriate (i.e. the nonlinear models did not explain more of the variability in the results).

The weaker relationships between the tillage translocation and slope gradient for the chisel plough and the field cultivator may be the result of the shape of the tillage tools, sweeps, which displace the soil in a different manner than either the tandem disc or the mouldboard plough, greater involvement of the operator in adjustments of tillage depth and speed, or simply the variability in the experiment as a whole.

Net downslope translocation was also analyzed to test the accuracy of the defined relationships. In theory, the value of â for net downslope translocation should be twice the magnitude of â determined for translocation, and the value of the y-intercept should equal zero. The coefficients were 0.868 as compared to 2 x 0.430 for the chisel plough; 1.286 as compared to 2 x 0.955 for the mouldboard plough; 1.973 as compared to 2 x 0.987 for the tandem disc; and 0.971 as compared to 2 x 0.313 for the field cultivator. Pairing data may not be appropriate because the value measured at a paired plot for tillage in one direction reflects the immediate area of the plot, but possibly the area in front of the plot were the tractor is situated. These larger areas of influence may not be suitable for pairing, particularly on asymmetrical curved slopes as those used in this study.

When the data from all tillage implements was normalized with respect to the intercepts á values and pooled, the r^2 value for a conventional tillage sequence defined by Lobb (1990) as one pass of mouldboard plough, two passes of tandem disc and one pass of field cultivator the r^2 value was 0.537. The data when grouped into this conventional tillage sequence indicated a reasonably good relationship between translocation and slope gradient.

Slope Curvature

To determine the relationship between tillage translocation and slope curvature only those plots where slope curvature was relatively large in comparison to slope gradient were selected for the calibration. This left too few plots to develop any relationships between slope curvature and tillage translocation for specific tillage implements. To provide a first approximation of ã, the data was normalized with respect to á values and pooled for analysis. Plots 6 (convex) from the M. Lobb site and plots 10 (concave) from the G. Lobb site were selected for the calibration. The relationship between slope curvature, ã, and á was:

ã = 0.145á,   (r^2 = 0.709)

Consequently, the proposed model for tillage translocation including the combined effects of slope gradient and curvature is:

$$\mathbf{T = á + âè + 0.145áö}$$

Consequently, the proposed model for tillage erosion, the net translocation out from a point in the landscape in the direction of tillage, including the combined effects of slope gradient and curvature is:

$$\mathbf{T = (á + âè_O) - (á + âè_I) + 0.145áö}$$

where $è_O$ is the output slope gradient, the forward difference; and$è_I$ is the input slope gradient, the backward difference. The rate of soil loss was calculated as the net translocation rate divided by the distance between the forward and backward midpoints. Elevation changes were calculated from the rate of soil loss and the soil bulk density.

Sensitivity Analysis

A sensitivity analysis was not conducted on the tillage erosion model because it was evident that for all four tillage implements tillage translocation was more sensitive to slope gradient than slope curvature based on the results of the calibration.

Performance Test

The tillage erosion model was tested to examine its performance under a set of hypothetical conditions.

On slopes of uniform gradient (Äè/Äx is constant, ö = 0) the soil mass translocated forward is constant, resulting in no net loss or accumulation except at the endpoints. At the starting point there is a net soil loss. At the stopping point there is a net accumulation of soil equal in magnitude to the loss at the starting point. The rate of soil loss or gain is determined by the length over which starting and stopping is defined. As more tillage passes are conducted in any one direction, the losses and gains increase proportionally. Tillage passes in opposing directions result in losses and accumulations at both endpoints. There is a net downslope translocation of soil resulting in a loss at the upper endpoint and a net accumulation at the lower endpoint. There is one exception, obviously net downslope translocation equals zero on level landscapes. On uniform slopes soil loss or accumulation at an endpoint eventually results in an irregularity in the surface. This irregularity (curvature) expands out from the endpoint as the number of tillage passes increases. Eventually, the surface can not be considered uniform.

On nonuniform, or curved, slopes (Äö/Äx … 0) the mass of soil translocated is not constant, therefore losses occur on convex slopes and accumulation occurs on concave slopes. On asymmetrical curved surfaces (Äö/Äx is not constant) the rate of soil loss is greatest in regions of the face where the rate of slope gradient increase is greatest, and the rate of accumulation is greatest in regions where the rate of slope gradient decrease is greatest.

Soil loss on convex surfaces and soil accumulation on concave surfaces causes a negative feedback that reduces the rate tillage erosion. Running the model over a 30 year period at high soil loss rates (1 cm yr^{-1}, . 135 t ha^{-1} yr^{-1}) did not greatly impact the performance of the model through the negative feedback, although 30 cm does represent a significant loss of topsoil. The impact of the negative feedback was greater on more complex landscapes.

Table 1: Chisel Plough Calibration Data (Treatments 1 and 2, M. Lobb Field Site)

Plot	Distance (m)	Elevation (m)	Slope Gradient (%)	Slope Curvature (% m^{-1})	Soil Bulk Density (kg m^{-3})	Tillage Depth (m)	Tillage Speed (m s^{-1})	Translocation	
								T (kg m^{-1})	ë (m)
1 1	154.7	0.25	0.71	-0.98	1453	0.175	2.56	27.4	
1 2	114.8	0.63	1.11	-0.84	1516	0.181	2.56	16.6	
1 3	84.6	2.12	7.34	0.19	1615	0.176	3.33	26.6	
1 4	80.2	2.47	8.72	0.31	1727	0.187	3.33	33.4	
1 5	63.5	3.76	5.61	-0.18	1784	0.166	2.44	50.2	
1 6	55.3	4.05	-0.25	0.93	1720	0.154	2.22	33.6	
1 7	48.3	3.72	-8.68	0.09	1660	0.142	2.00	29.8	
1 8	37.6	2.53	-11.58	-0.15	1617	0.172	2.54	26.5	
1 9	19.0	0.98	-4.54	-0.57	1579	0.173	2.54	28.9	
1 10	1.7	0.18	-4.10	-1.17	1595	0.148	2.51	33.3	
2 1	155.2	0.20	-0.39	-1.53	1453	0.170	2.55	98.8	
2 2	115.8	0.58	-0.92	-1.32	1516	0.179	2.84	30.0	
2 3	85.7	1.96	-7.05	-1.75	1615	0.159	2.56	17.6	
2 4	81.5	2.29	-7.15	-0.15	1727	0.140	2.56	19.7	
2 5	64.6	3.66	-5.37	-0.05	1784	0.138	2.81	19.8	
2 6	56.6	3.97	-0.02	1.13	1720	0.146	3.02	27.2	
2 7	50.4	3.72	8.56	0.22	1660	0.193	3.33	34.1	
2 8	39.8	2.55	10.94	0.14	1617	0.190	2.50	29.7	
2 9	20.8	0.91	4.30	-1.01	1579	0.195	2.50	32.3	
2 10	3.7	0.18	4.11	-0.95	1595	0.187	2.51	24.6	

Table 2: Mouldboard Plough Calibration Data (Treatments 3 and 4, M. Lobb Field Site)

Plot	Distance (m)	Elevation (m)	Slope Gradient (%)	Slope Curvature (% m^{-1})	Soil Bulk Density (kg m^{-3})	Tillage Depth (m)	Tillage Speed (m s^{-1})	Translocation T (kg m^{-1})	ë (m)
3 1	156.5	0.19	-0.68	-1.09	1453	0.183	1.80	28.7	
3 2	117.5	0.53	0.97	1.10	1516	0.202	1.81	33.3	
3 3	87.2	1.80	6.74	-0.35	1615	0.203	1.83	42.6	
3 4	83.6	2.05	7.33	0.22	1727	0.203	1.76	45.3	
3 5	65.5	3.56	6.45	1.08	1784	0.220	1.76	59.0	
3 6	58.7	3.84	0.95	2.19	1720	0.266	1.60	55.0	
3 7	53.7	3.68	-7.17	2.29	1660	0.266	1.43	51.6	
3 8	43.2	2.49	-11.97	0.29	1617	0.216	1.40	24.7	
3 9	23.3	0.80	-4.26	0.04	1579	0.240	1.60	50.8	
3 10	6.9	0.11	-3.85	-0.41	1595	0.230	1.68	33.7	
4 1	157.2	0.17	0.39	-0.38	1453	0.202	1.79	20.5	
4 2	118.4	0.45	-0.57	0.31	1516	0.222	1.80	21.0	
4 3	88.3	1.65	-6.10	-0.30	1615	0.210	1.77	28.1	
4 4	84.6	1.92	-7.19	0.90	1727	0.206	1.77	46.6	
4 5	67.6	3.37	-6.71	1.98	1784	0.206	1.59	47.1	
4 6	60.0	3.68	-0.93	2.04	1720	0.232	1.63	39.5	
4 7	55.3	3.55	2.13	2.66	1660	0.230	1.67	53.3	
4 8	45.3	2.32	10.26	-6.96	1617	0.234	2.05	42.4	
4 9	24.9	0.79	5.34	0.38	1579	0.218	1.83	39.7	
4 10	8.7	0.12	4.13	0.23	1595	0.230	1.59	39.1	

Table 3: Tandem Disc Calibration Data (Treatments 1 and 2, G. Lobb Field Site)

Plot	Distance (m)	Elevation (m)	Slope Gradient (%)	Slope Curvature (% m^{-1})	Soil Bulk Density (kg m^{-3})	Tillage Depth (m)	Tillage Speed (m s^{-1})	Translocation T (kg m^{-1})	Translocation ë (m)
1 1	119.7	4.50	2.02	-0.44	1058		0.87	23.0	
1 2	110.1	4.91	5.86	-1.18	1077		0.98	30.4	
1 3	105.2	5.20	5.27	-0.95	1086		0.98	29.1	
1 4	95.5	5.69	3.78	-0.13	1095		0.93	21.6	
1 5	90.0	5.72	-2.44	0.29	1094		0.93	19.5	
1 6	82.5	5.32	-9.74	0.73	1118		0.77	10.3	
1 7	71.2	3.91	-12.90	-0.39	1133		0.46	10.6	
1 8	67.9	3.47	-12.02	-1.29	1112		0.46	9.2	
1 9	54.2	2.29	-5.56	-0.96	1075		0.87	20.8	
1 10	52.2	2.23	-0.90	-1.19	1080		0.87	18.9	
1 11	43.4	2.33	3.59	-0.78	1069		0.93	29.9	
1 12	33.7	2.66	-4.08	0.87	1067		0.87	26.9	
2 1	120.6	4.28	-3.80	-0.26	1058		0.82	24.2	
2 2	110.1	4.73	-5.75	-1.30	1077		0.87	22.5	
2 3	104.9	5.03	-5.42	-1.19	1086		0.82	23.0	
2 4	94.6	5.58	-3.35	0.15	1095		0.77	27.2	
2 5	89.0	5.68	3.09	-1.22	1094		0.87	31.5	
2 6	81.3	5.33	9.73	0.92	1118		0.93	32.9	
2 7	71.1	4.01	13.20	-0.54	1133		0.98	34.9	
2 8	67.8	3.56	9.32	0.85	1112		1.03	36.1	
2 9	54.2	2.41	5.44	-0.89	1075		0.98	29.7	
2 10	52.2	2.35	0.78	-1.26	1080		0.98	22.5	
2 11	43.4	2.51	-4.37	-0.84	1069		0.62	33.3	
2 12	33.6	2.95	2.14	1.01	1067		0.62	28.4	

Table 4: Field Cultivator Calibration Data (Treatments 3 and 4, G. Lobb Field Site)

Plot	Distance (m)	Elevation (m)	Slope Gradient (%)	Slope Curvature (% m^{-1})	Soil Bulk Density (kg m^{-3})	Tillage Depth (m)	Tillage Speed (m s^{-1})	Translocation	
								T (kg m^{-1})	ë (m)
3 1	124.8	3.94	1.49	-0.26	1123		1.85	34.2	
3 2	114.4	4.27	5.01	-0.29	1143		2.16	39.8	
3 3	108.2	4.63	5.25	0.04	1153		2.06	23.9	
3 4	93.5	5.37	2.65	0.41	1163		2.21	25.6	
3 5	86.2	5.43	-3.01	0.99	1161		2.11	25.3	
3 6	76.5	4.77	-10.12	0.45	1187		1.23	25.4	
3 7	69.4	3.89	-13.19	-0.05	1203		1.13	30.2	
3 8	66.0	3.47	-10.27	-0.41	1181		1.39	26.6	
3 9	54.3	2.53	-4.89	-0.80	1141		1.80	34.7	
3 10	52.2	2.47	-0.28	-1.38	1147		1.70	31.4	
3 11	41.5	2.78	4.76	-0.27	1135		1.90	33.6	
3 12	30.8	3.22	-2.67	0.65	1132		1.95	28.7	
4 1	125.5	3.71	-2.21	-0.40	1123		2.21	29.3	
4 2	114.4	4.22	-5.98	-0.44	1143		2.00	25.1	
4 3	108.2	4.61	-5.63	0.04	1153		2.06	24.1	
4 4	95.2	5.17	-2.74	0.26	1163		1.90	25.6	
4 5	85.3	5.25	2.80	1.00	1161		2.31	26.4	
4 6	75.5	4.61	8.91	0.63	1187		1.90	19.8	
4 7	69.3	3.90	11.53	-1.86	1203		2.21		
4 8	66.0	3.53	10.85	-1.06	1181		2.31	34.8	
4 9	54.3	2.55	5.84	-0.97	1141		2.00	25.9	
4 10	52.2	2.48	1.00	-1.25	1147		1.90	22.8	
4 11	41.5	2.71	-3.86	-0.21	1135		1.70	34.1	
4 12	30.7	3.13	-0.26	0.59	1132		2.06	21.9	

Figure 1: Chisel plough tillage translocation related to slope gradient (T_{CP} = 25.50 + 0.430 è, based on plots 3, 4 and 8).

Figure 2: Mouldboard plough tillage translocation related to slope gradient (T_{MP} = 34.61 + 0.955 è, based on plots 3, 4 and 8).

Figure 3: Tandem disc tillage translocation related to slope gradient (T_{TD} = 24.78 + 0.987 è, based on plots 2, 3, 7 and 8).

Figure 4: Field cultivator tillage translocation related to slope gradient (T_{FC} = 29.84 + 0.313 è, based on plots 2, 3, 7 and 8).

MODEL VALIDATION

The proposed tillage erosion model was validated using data collected during two preceding studies, *Management of Farm Field Variability I. Quantification of Soil Loss in Complex Topography* conducted in Brant County (Kachanoski et al., 1992) and *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* conducted in Huron County (Lobb et al., 1992b). Resident ^{137}Cs radioactivity was used to estimate soil redistribution within the landscapes of the field sites. The resident ^{137}Cs data from the latter study set was not previously reported. These estimates of soil loss and accumulation were compared to those predicted by the tillage erosion model based on the topography of the field sites.

Estimation of Soil Redistribution Using Resident ^{137}Cs Radioactivity

The method used to estimate soil loss and accumulation in this study was described by Kachanoski et al. (1992). The rate of soil loss was calculated using the following function between the fraction of ^{137}Cs residing in the soil, the initial ^{137}Cs (corrected for radioactive decay) and the years between initial and final sampling:

$$\mathbf{L = M / R\ (1 - (C_n/C_o)^{1/n})}$$

where L is the average annual rate of soil loss (kg m^{-2} yr^{-1}); M is the specific soil mass of the till layer in which the ^{137}Cs is distributed (kg m^{-2}, the product of the soil bulk density and the depth of the till layer); R is the enrichment ratio (ratio of ^{137}Cs concentration (Bq kg^{-1}) in the sediment versus the till layer); C_n is the level of resident ^{137}Cs radioactivity (Bq m^{-2}) at t = n years (final sampling); C_o is the initial level resident ^{137}Cs radioactivity (Bq m^{-2}) at t = 0 years. Consequently, the rate of soil loss is a function of the fraction of ^{137}Cs remaining, C_n/C_o, and the number of years over which that erosion rate was occurring. All values of ^{137}Cs radioactivity are corrected for radioactive decay to the date of final sampling. Further explanation and the development of this equation are given in Kachanoski et al. (1992).

Negative values of soil loss were interpreted as soil accumulation, although negative soil loss values were not discussed by Kachanoski et al. (1992).

The relationship presented in the above equation is a power function in time opposed to the linear relationship suggested by de Jong et al. (1982, 1983). The power function is considered superior to the linear function in that it accounts for the dilution of the ^{137}Cs in the till layer through soil loss and subsequent incorporation of ^{137}Cs poor subsoil into the till layer. It gives a very similar prediction as the more complex model described by Kachanoski and de Jong (1984). A comparison of the two methods is presented in Kachanoski et al. (1992).

Initial levels of resident ^{137}Cs radioactivity, C_o, can be measured directly from soil samples taken at t = 0. Where initial levels of ^{137}Cs radioactivity, C_o, are not available, they have to be estimated based on estimated rates of atmospheric deposition and radioactive decay. Resident ^{137}Cs radioactivity reflects the pattern of soil redistribution by erosion processes since the atomic tests of the late 1950s early 1960s which are the source of ^{137}Cs. Therefore, in the latter case n equals the number of years between 1960 and the year of sampling.

Kachanoski (1987) reported that accumulated atmospheric deposition of ^{137}Cs (corrected for subsequent radioactive decay) should be approximately 2700 Bq m^{-2} in 1985. Levels measured at two noneroded sites (one permanent grass cover the other a forested site) at Guelph in 1985 by Kachanoski (1987) were slightly lower than 2700 Bq m^{-2}, about 2600 Bq m^{-2}. In addition, there appeared to be slightly greater ^{137}Cs accumulation in the lower slope position of the grassed site which may be associated with variable surface runoff accumulation or snowfall accumulation. Consequently, a single initial value of resident ^{137}Cs radioactivity should be used with caution because it may result in the over estimation of soil loss from landscapes where rainfall exists in runoff, and overestimation of soil accumulation in landscape positions where runoff accumulates. Regional differences in total accumulated ^{137}Cs can result from temporal and spatial variability in rainfall since the late 1950's.

In addition to the following assumptions: 1) atmospheric deposition of ^{137}Cs within the landscape has been uniform; 2) total deposition of ^{137}Cs and losses through decay are know or can be accurately estimated; and 3) changes in resident ^{137}Cs are a result of soil redistribution; the use of resident ^{137}Cs to infer soil redistribution within landscapes by soil erosion processes assumes that point resident ^{137}Cs measurements provide accurate estimates of soil loss and accumulation.

Lobb (1990) identified that the level of ^{137}Cs radioactivity at a point in the landscape can change without a change in soil mass at that point. The concentration of ^{137}Cs in the soil translocated into a point by tillage is not necessarily the same as that translocated out from that point. The implication of this fact is that resident ^{137}Cs may not be a highly accurate indicator of soil redistribution, particularly in very complex topography where the rate of redistribution is high and/or when the duration of redistribution is long. Estimates of soil redistribution based on point measurements of resident ^{137}Cs will underestimate the degree of soil loss and accumulation and overestimate the extent of soil loss and accumulation. As long as the layer of soil being redistributed is uniform with depth, i.e. the soil below the till layer has the same concentration as the soil within the till layer, the effect of soil redistribution estimates is predictable and possibly correctable. Obviously, in areas of severe soil loss ^{137}Cs poor subsoil will be mixed into the till layer. As this occurs soil loss is further underestimated, the inaccuracy increasing as the degree of ^{137}Cs depletion increases. This phenomenon will impact the validation of the tillage erosion model, as well as the validation of any erosion models (e.g. WEPP). For the purposes of this study, resident ^{137}Cs is considered to be the most accurate method of validation available.

Brant County Field Site

Resident ^{137}Cs radioactivity analysis was conducted on soil samples collected in 1971 and again in 1985 from a farm field in Brant County. The measurements of resident ^{137}Cs and estimates of soil loss were reported in *Management of Farm Field Variability I. Quantification of Soil Loss in Complex Topography* (Kachanoski et al., 1992).

Site Description

The Brant County field site has been described in Kachanoski et al. (1992). A more detailed description can be found in the Ph.D. Thesis of L.S. Crosson (1972).

The Brant site is a 80 m by 190 m section of field which is characterized as topographically complex with slope gradients exceeding 20 %. Two prominent ridges traverse the width of the field section (see Figure 6). The larger of the two ridges is somewhat divergent with cross slope of up to 3 %. The smaller ridge is more divergent with cross slopes exceeding 5 %. Soil samples were taken on a 10 m by 10 m grid, 190 m in length and 80 m in width consisting of 9 columns/transects and 20 rows. The entire soil profile at each grid point was sampled and analyzed providing very accurate measures of total resident ^{137}Cs.

Kachanoski et al. (1992) reported^{137}Cs mass balance indicated that over the 15 years period of the study the amount of cesium lost through off-field transport processes (wind and water erosion) was not significant. Whereas the amount of cesium redistributed within the field by in-field transport processes (wind, water and tillage erosion) was considerable.

Cropping and Tillage History

The Brant site was in hay-pasture for a number of years prior to the 1971 sampling, and was possibly always under this management. In 1972 the site was ploughed and planted to corn for 6 years. It was then returned to a hay-pasture management with no subsequent tillage. Therefore, it has been assumed that all the redistribution of soil within the field site occurred over a 6 year, or possibly 7 year (including 1 year for establishment of the hay crop), period. Tillage practices are assumed to be conventional, consisting of mouldboard plough fall primary tillage and spring secondary tillage.

The pattern of tillage and cropping operations is not known but presumed to be parallel with the length of the field and therefore the transects. The use of the ^{137}Cs data in this study assumes that during the erosion period that tillage direction was always parallel to the transects. This is probably not true since secondary tillage operations are often conducted at right angles to the direction of primary tillage and sometimes across the diagonal of the field. Since the transects follow the length of the field, the preferred, and most followed direction, would be parallel to the transects.

Validation

For the purposes of validating the tillage erosion model, a single transect was generated from this data set. Of the nine transects, three were selected to generate a landscape profile of elevation, ^{137}Cs accumulation and soil accumulation - transects 3 through 5 (see Tables 5 and 6). These transects were in a region of the field area where lateral translocation was expected to be relatively minor. Values of elevation, ^{137}Cs accumulation and soil accumulation for transects 3 to 5 were averaged to generate this profile.

The complete data set will be used in the future to validate the 3-dimensional version of the tillage model which will include lateral tillage translocation.

Figures 8 and 9 indicate that there has been a significant redistribution of ^{137}Cs and soil within the landscape with losses generally occurring on the upper slope landscape positions and accumulations generally occurring in lower slope landscape positions.

Figure 10 compares the values of soil accumulation predicted by the tillage erosion model to those estimated using resident ^{137}Cs. In determining the accuracy of the model the endpoints of the transects were exclude from the regression analysis, but are present in the Figure 10. The endpoints represent the soil loss and accumulation that results from starting and stopping tillage operations. These values reflect the cumulative loss and accumulation along the transect (the net dumping of soil at each end of the field) not the topography at those points.

The relationship between predicted and estimated rates of soil accumulation on the larger ridge, points 2 through 11, is:

$$\mathbf{P = 1.369 + 0.371 * E \quad (r^2 = 0.805)}$$

where P is the soil accumulation rate predicted by the model (kg m^{-2}), and E is the soil accumulation rate estimated from the change in resident ^{137}Cs radioactivity (kg m^{-2}) (see Table 7 and Figure 11).

The relationship between predicted and estimated rates of soil accumulation including the second ridge, points 2 through 16, is:

$$\mathbf{P = 1.849 + 0.389 * E \quad (r^2 = 0.737)}$$

The second ridge is much smaller than first and much more divergent, therefore planing by the tillage equipment will have been proportionately greater and lateral translocation will have resulted in greater losses.

The relationship between predicted and estimated rates of soil accumulation for the entire profile, excluding the two endpoints, points 2 through 19, is:

$$\mathbf{P = 0.235 + 0.245 * E \quad (r^2 = 0.513)}$$

The inclusion of points 16 through 19 add a very complex piece of the landscape where the cross slope gradient exceeds the gradient along the profile. Lateral translocation is expected to result in estimated levels of soil accumulation greater than predicted in this convergent portion of the landscape.

The relationship between predicted and estimated rates of soil accumulation on the larger ridge, points 2 through 11, when the values for è and ö calculated by Kachanoski et al. (1992) are used in calculating the predicted values rather than è and ö calculated from simple differences between the plot elevations, is:

$$\mathbf{P = 3.237 + 0.648 * E \quad (r^2 = 0.829)}$$

There is a notable difference between the predictions using the two sets of topographic data, with the values of è and ö calculated in this study providing a more accurate prediction of the soil accumulation estimates. The reason for the difference is not known since the method used by Kachanoski et al. (1992) to calculate è and ö is presumed to be more accurate. Kachanoski et al. (1992) calculated è and ö at each sample point based on local elevations (9 points within a 3 m radius). The difference may simply reflect the degree of experimental error in the validation, the error associated with the use of resident ^{137}Cs to estimate soil erosion, or possibly the effect of characterizing topography at one scale and relating it to a process that operates at a different scale within the landscape. This suggests that the simpler method, because it characterizes è and ö at a larger scale, may be more appropriate for modelling tillage erosion in this situation.

The asymmetry of the ridge does not appear to have affected the validation. This may be due to the relatively large size of the ridge in comparison to the size of tillage equipment.

Figure 6: Topography of the Brant field site in 1985, average elevations of transects 1 to 3, 4 to 6, 7 to 9, and 1 to 9.

Figure 7: Accumulation of ^{137}Cs at the Brant field site between 1971 and 1985, average values for transects 1 to 3, 4 to 6, 7 to 9, and 1 to 9.

Figure 8: Landscape profile of elevation and accumulation of ^{137}Cs generated for the Brant field site from transects 3 to 5.

Figure 9: Landscape profile of elevation and soil accumulation rate generated for the Brant field site from transects 3 to 5.

Figure 10: Landscape profile of estimated and predicted soil accumulation rates at the Brant field site - estimated using resident ^{137}Cs and predicted with the tillage erosion model.

Figure 11: Comparison of soil accumulation rates at the Brant field site predicted with the tillage erosion model and those estimated using resident ^{137}Cs radioactivity.

Table 5a: Predicted Soil Redistribution at the Brant County Field Site (Tillage Direction `1 to 20')

	Distance (m)	Elevation (m)	Slope Gradient w.r.t. Tillage Direction (%)		Slope Curvature (% m^{-1})	Predicted Net Tillage Translocation Output-Input (kg m^{-1} per tillage pass)			Predicted Rate of Soil Accumulation (kg m^{-2} per tillage pass)				Rate of Soil Accumulation‡ (cm per tillage sequence)
			Input	Output		Mouldboard Plough	Tandem Disc	Field Cultivator	Mouldboard Plough	Tandem Disc	Field Cultivator	Tillage Sequence †	
1	0	5.46		-20.0		15.5	5.0	23.6	-3.10	-1.01	-4.72	-9.8	-0.76
2	10	7.46	-20.0	-23.8	-0.38	-5.5	-5.1	-2.8	0.55	0.51	0.28	1.8	0.14
3	20	9.84	-23.8	-14.4	0.93	13.6	12.6	7.0	-1.36	-1.26	-0.70	-4.6	-0.35
4	30	11.28	-14.4	-4.8	0.97	14.1	13.0	7.2	-1.41	-1.30	-0.72	-4.7	-0.36
5	40	11.76	-4.8	11.1	1.58	23.1	21.3	11.8	-2.31	-2.13	-1.18	-7.8	-0.60
6	50	10.65	11.1	26.4	1.53	22.3	20.6	11.4	-2.23	-2.06	-1.14	-7.5	-0.58
7	60	8.01	26.4	24.4	-0.20	-2.9	-2.7	-1.5	0.29	0.27	0.15	1.0	0.08
8	70	5.57	24.4	18.3	-0.61	-8.9	-8.3	-4.6	0.89	0.83	0.46	3.0	0.23
9	80	3.74	18.3	11.2	-0.71	-10.3	-9.5	-5.3	1.03	0.95	0.53	3.5	0.27
10	90	2.62	11.2	5.2	-0.60	-8.8	-8.1	-4.5	0.88	0.81	0.45	3.0	0.23
11	100	2.11	5.2	-4.8	-0.99	-14.5	-13.4	-7.4	1.45	1.34	0.74	4.9	0.37
12	110	2.58	-4.8	-4.1	0.07	1.0	0.9	0.5	-0.10	-0.09	-0.05	-0.3	-0.03
13	120	2.99	-4.1	8.7	1.28	18.6	17.2	9.5	-1.86	-1.72	-0.95	-6.3	-0.48
14	130	2.12	8.7	11.4	0.27	3.9	3.6	2.0	-0.39	-0.36	-0.20	-1.3	-0.10
15	140	0.98	11.4	0.2	-1.12	-16.3	-15.1	-8.4	1.63	1.51	0.84	5.5	0.42
16	150	0.96	0.2	-5.2	-0.54	-7.9	-7.3	-4.0	0.79	0.73	0.40	2.6	0.20
17	160	1.48	-5.2	-7.9	-0.27	-3.9	-3.6	-2.0	0.39	0.36	0.20	1.3	0.10
18	170	2.27	-7.9	-7.2	0.07	1.0	0.9	0.5	-0.10	-0.09	-0.05	-0.3	-0.03
19	180	2.99	-7.2	-4.1	0.32	4.6	4.3	2.4	-0.46	-0.43	-0.24	-1.6	-0.12
20	190	3.40	-4.1			-30.7	-20.8	-28.6	6.15	4.15	5.71	20.2	1.55

† Conventional tillage sequence consisting of mouldboard plough, tandem disc (double pass), field cultivator (single pass).

‡ Based on a field average soil bulk density of 1300 kg m^{-3}.

Table 5b: Predicted Soil Redistribution at the Brant County Field Site (Opposing Tillage Direction `20 to 1')

	Distance (m)	Elevation (m)	Slope Gradient w.r.t. Tillage Direction (%)		Slope Curvature (% m^{-1})	Predicted Net Tillage Translocation Output-Input (kg m^{-1} per tillage pass)			Predicted Rate of Soil Accumulation (kg m^{-2} per tillage pass)				Rate of Soil Accumulation‡ (cm per tillage sequence)
			Input	Output		Mouldboard Plough	Tandem Disc	Field Cultivator	Mouldboard Plough	Tandem Disc	Field Cultivator	Tillage Sequence †	
1	0	5.46	20.0			-53.7	-44.5	-36.1	10.74	8.90	7.22	35.8	-2.75
2	10	7.46	23.8	20.0	-0.38	-5.5	-5.1	-2.8	0.55	0.51	0.28	1.8	0.14
3	20	9.84	14.4	23.8	0.93	13.6	12.6	7.0	-1.36	-1.26	-0.70	-4.6	-0.35
4	30	11.28	4.8	14.4	0.97	14.1	13.0	7.2	-1.41	-1.30	-0.72	-4.7	-0.36
5	40	11.76	-11.1	4.8	1.58	23.1	21.3	11.8	-2.31	-2.13	-1.18	-7.8	-0.60
6	50	10.65	-26.4	-11.1	1.53	22.3	20.6	11.4	-2.23	-2.06	-1.14	-7.5	-0.58
7	60	8.01	-24.4	-26.4	-0.20	-2.9	-2.7	-1.5	0.29	0.27	0.15	1.0	0.08
8	70	5.57	-18.3	-24.4	-0.61	-8.9	-8.3	-4.6	0.89	0.83	0.46	3.0	0.23
9	80	3.74	-11.2	-18.3	-0.71	-10.3	-9.5	-5.3	1.03	0.95	0.53	3.5	0.27
10	90	2.62	-5.2	-11.2	-0.60	-8.8	-8.1	-4.5	0.88	0.81	0.45	3.0	0.23
11	100	2.11	4.8	-5.2	-0.99	-14.5	-13.4	-7.4	1.45	1.34	0.74	4.9	0.37
12	110	2.58	4.1	4.8	0.07	1.0	0.9	0.5	-0.10	-0.09	-0.05	-0.3	-0.03
13	120	2.99	-8.7	4.1	1.28	18.6	17.2	9.5	-1.86	-1.72	-0.95	-6.3	-0.48
14	130	2.12	-11.4	-8.7	0.27	3.9	3.6	2.0	-0.39	-0.36	-0.20	-1.3	-0.10
15	140	0.98	-0.2	-11.4	-1.12	-16.3	-15.1	-8.4	1.63	1.51	0.84	5.5	0.42
16	150	0.96	5.2	-0.2	-0.54	-7.9	-7.3	-4.0	0.79	0.73	0.40	2.6	0.20
17	160	1.48	7.9	5.2	-0.27	-3.9	-3.6	-2.0	0.39	0.36	0.20	1.3	0.10
18	170	2.27	7.2	7.9	0.07	1.0	0.9	0.5	-0.10	-0.09	-0.05	-0.3	-0.03
19	180	2.99	4.1	7.2	0.32	4.6	4.3	2.4	-0.46	-0.43	-0.24	-1.6	-0.12
20	190	3.40		4.1		38.5	28.8	31.1	-7.71	-5.77	-6.22	-25.5	1.96

† Conventional tillage sequence consisting of mouldboard plough, tandem disc (double pass), field cultivator (single pass).

‡ Based on a field average soil bulk density of 1300 kg m^{-3}.

Table 6: Estimated Soil Redistribution at the Brant County Field Site Based on Resident ^{137}Cs Radioactivity

	Distance (m)	Transect 3				Transect 4				Transect 5				Average Estimated Rate of Soil Accumulation (kg m^{-2} yr^{-1})
		Resident ^{137}Cs Radioactivity (Bq m^{-2})			Estimated Soil Gain† (kg m^{-2} yr^{-1})	Resident ^{137}Cs Radioactivity (Bq m^{-2})			Estimated Soil Gain† (kg m^{-2} yr^{-1})	Resident ^{137}Cs Radioactivity (Bq m^{-2})			Estimated Soil Gain† (kg m^{-2} yr^{-1})	
		1971	1985	Gain		1971	1985	Gain		1971	1985	Gain		
1	0	2033	2315	282	4.3	1261	1913	652	14.2	2683	2425	-257	-3.3	5.1
2	10	1320	1357	37	0.9					2064	1558	-505	-9.1	-4.1
3	20	1338	1319	-18	-0.5	1022	1022	0	0.0	1973	1218	-754	-15.4	-5.3
4	30	2004	1272	-731	-14.5	1921	729	-1191	-29.9	1080	607	-472	-18.3	-20.9
5	40	1448	924	-523	-14.4	2634	885	-1748	-33.4	1228	633	-594	-20.9	-22.9
6	50	1507	883	-623	-17.0	1540	863	-676	-18.4	1363	691	-671	-21.4	-18.9
7	60	2233	3092	859	11.0	2436	2056	-379	-5.5	2783	1355	-1427	-22.6	-5.7
8	70	2675	2617	-57	-0.7	1923	1952	29	0.5	1517	1525	8	0.2	-0.0
9	80	3000	3783	783	7.8	1973	2296	323	5.1	1164	1720	556	13.3	8.7
10	90	1484	1794	310	6.4	1874	2622	748	11.4					8.9
11	100	1817	2380	563	9.1	2216	2032	-181	-2.8	2219	2473	254	3.6	3.3
12	110	1581	1667	86	1.8	2130	2242	112	1.7	2454	1082	-1371	-25.5	-7.4
13	120	1374	614	-759	-25.2	2291	1634	-656	-10.9	2145	1281	-863	-16.4	-17.5
14	130	2530	1481	-1048	-17.0	2762	1800	-961	-13.7	1602	2360	758	13.2	-5.9
15	140					2540	2230	-309	-4.3					-4.3
16	150	1349	2841	1492	26.0					1661	2753	1092	17.3	21.6
17	160					1762	2083	321	5.6					5.6
18	170					1717	3528	1811	25.1	1506	776	-729	-20.9	2.1
19	180	966	1847	881	22.4	2208	3008	800	10.4	984	1241	257	7.8	13.6
20	190	2000	2739	739	10.6	1067	2300	1233	26.8	1791	1128	-622	-14.8	7.6

† Estimated rate of soil accumulation calculated using Equation X given a constant soil bulk density of 1300 kg m^{-3} and tillage depth of 0.178 m.

Table 7: Estimated and Predicted Soil Redistribution at the Brant County Field Site

	Distance (m)	Estimated Rate of Soil Accumulation (kg m^{-2} per tillage sequence)			Average Estimated Rate of Soil Accumulation (kg m^{-2} yr^{-1})
		Direction `1 to 20'	Direction `20 to 1'	Annual Average†	
1	0	-9.8	35.8	13.0	5.1
2	10	1.8	1.8	1.8	-4.1
3	20	-4.6	-4.6	-4.6	-5.3
4	30	-4.7	-4.7	-4.7	-20.9
5	40	-7.8	-7.8	-7.8	-22.9
6	50	-7.5	-7.5	-7.5	-18.9
7	60	1.0	1.0	1.0	-5.7
8	70	3.0	3.0	3.0	-0.0
9	80	3.5	3.5	3.5	8.7
10	90	3.0	3.0	3.0	8.9
11	100	4.9	4.9	4.9	3.3
12	110	-0.3	-0.3	-0.3	-7.4
13	120	-6.3	-6.3	-6.3	-17.5
14	130	-1.3	-1.3	-1.3	-5.9
15	140	5.5	5.5	5.5	-4.3
16	150	2.6	2.6	2.6	21.6
17	160	1.3	1.3	1.3	5.6
18	170	-0.3	-0.3	-0.3	2.1
19	180	-1.6	-1.6	-1.6	13.6
20	190	20.2	-25.5	-2.6	7.6

† Estimated annual rate of soil accumulation based average of two tillage sequences conducted in opposing directions.

Huron County Field Site

Resident ^{137}Cs radioactivity was conducted on soil samples taken from two farm field sites in Huron County. These soil samples were collected during the study *Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage* (Lobb et al., 1992b), in 1990 during the primary tillage translocation experiments at the M. Lobb site, and in 1991 during the secondary tillage translocation experiments at the G. Lobb site. It was the tillage translocation data collected from these two sites was used to calibrate the tillage erosion model. To date only the resident ^{137}Cs radioactivity from the M. Lobb site is complete. The data from the G. Lobb site will be used for further validation in the future.

Site Description

The Huron County field site is described above in the section entitled Calibration and in greater detail in Lobb et al. (1992b).

The section of the field where the primary tillage treatments were conducted was about 20 m in width and 160 m in length. The four tillage treatments which represent transects were spaced at about 5 m centres running adjacent and parallel with the fence row. It is important to note that the field entrance was near treatment 4 plot 1. The position of the entrance imposes a tillage pattern whereby tillage operations follow in the direction from plot 1 to plot 10 of the treatments. The cross slope gradient is less than 1 %, therefore, lateral translocation was considered negligible.

Cropping and Tillage History

The cropping histories for both Huron County field sites are presented in Table 10. In the 1960's both field sites changed from forage-grain cropping rotations to more intensive row crop rotations, including wheat, corn, white beans, and soybeans. The tillage practices associated with the crops were what would be considered conventional - mouldboard ploughing in the fall and secondary tillage in the spring with discs and field cultivators. Although cropping and tillage practices were conventional, they differed somewhat between fields, and over time for each field. Each field has been operated by more than one farmer since 1960, each using a different set of equipment. The more intensive cropping practices of the 1970's and 1980's demanded more intensive tillage practices, larger tillage equipment, usually operated at greater speeds and depths, larger tractors, more secondary tillage operations, and additional field cultivation during the growing season for white beans and often corn. These intensive cropping and tillage practices are presumed to be responsible for the severe soil loss observed within the two field sites on the upper slope landscape positions.

Resident ^{137}Cs Data

The estimated level of resident ^{137}Cs radioactivity at the time of soil sampling, assuming no erosion had taken place, would be approximately 2500 Bq m^{-2}. This estimate is based on the `noneroded' level of 2700 Bq m^{-2} in 1985 (Kachanoski, 1987), the loss through radioactive decay (decay constant = 0.023 yr^{-1}), and the annual gain through atmospheric deposition of 37 Bq m^{-2} (Butler, 1980).

Samples #3 and #4 from each of the 10 plots of each of the 4 transect were analyzed for resident ^{137}Cs radioactivity. A total of 80 samples from the M. Lobb site were analyzed. 96 samples from the G. Lobb site are being analyzed for resident ^{137}Cs radioactivity.

The accuracy of this data depends on the assumption that the depth of samples #3 and #4 taken at each plot contains the total depth of ^{137}Cs distribution. The average depth of chisel ploughing was 16.9 cm compared to the average depth of mouldboard ploughing 22.1 cm. The shallower depth of tillage and therefore sampling may be the cause of the 17.5 % lower average level of ^{137}Cs. This is clearly more of a problem in the lower slope positions where deposition may be occurring. Since there was no statistically significant difference between the two subsets of ^{137}Cs data no attempt was made to correct for this possible problem.

Although the magnitudes of ^{137}Cs may be inaccurate, the data still exhibits an obvious pattern of greater ^{137}Cs loss on the upper slope positions relative to the lower slope positions. Relative to the level of 2500 Bq m^{-2} the whole profile appears to have lost ^{137}Cs. Greater sampling depths in the lower slope positions may have resulted in higher levels in these positions, possibly even accumulation relative to 2500 Bq m^{-2}. It is also possible that the level of 2500 Bq m^{-2} is too high for this region of southwestern Ontario.

Validation

The landscape profile of resident ^{137}Cs used in the validation of the tillage erosion model was generated by averaging the values for each respective plot of transects 1 through 4 (see Tables 8 and 9 and Figure 14).

Figure 14 indicates that there was significant loss of ^{137}Cs throughout the landscape and that there is a relatively greater rate of loss on the upper slope landscape positions.

Soil accumulation was estimated using three different calculations of specific soil mass, M: #1) based on the values of soil bulk density and maximum mouldboard plough tillage depth reported in Table 9; #2) based on estimates of soil bulk density and tillage depth based on reported maximums and position within the landscape - both increasing with increasing elevation; and #3) based on field averages for soil bulk density (1627 kg m^{-3}) and mouldboard plough tillage depth (23.0 cm) (see Figure 15). All three estimates using different values of specific soil mass produced nearly identical patterns of soil redistribution - greater soil loss associated with the upper slope landscape positions. The peak soil loss appears to be slightly offset from the crest of the hill - positioned towards the steeper slope face.

The difference in resident ^{137}Cs and soil loss at plots 3 and 4, which are only 4 m apart on the slope (plot #4 at 82.5 m and plot #3 at 86.5 m), is evidence of either the actual variability in ^{137}Cs or the experimental error in the method of sample collection.

The patterns of soil accumulation rates estimated using ^{137}Cs and predicted using the model both have considerable greater rates of soil loss associated with the upper slope landscape positions (see Figure 16). The model predicts the accumulation of soil in the lower slope landscape position where as the values of ^{137}Cs indicate soil loss in these positions as well. This could be the result of an overestimation of 2500 Bq m^{-2} for a noneroded site, the level of resident ^{137}Cs would have to be approximately 2000 Bq m^{-2} rather than 2500 Bq m^{-2} to agree with the predictions of soil accumulation in these positions. The other possible cause is the diffusion of ^{137}Cs poor subsoil from erosional areas through tillage translocation described above. Another possible cause is additional soil redistribution by wind and water erosion or lateral tillage translocation away from the fenceline down the profile of the ridge which diverges slightly. Regardless, there is clearly defined pattern of variable soil redistribution associated with landscape position, erosional phases situated on convex upper slope landscape positions. Severe soil loss, based on soil profiles, was only observed on the upper slope landscape positions. In the lower slope landscape positions it appeared to accumulation of soil.

Although soil bulk density and tillage depths were quite variable, 1400 to 1800 kg m^{-3} and 20 to 27 cm, there were was an obvious increase in both soil bulk density and tillage depth on the upper slope positions. Samples were removed to in excess of the tillage depth to remove all of the chloride tracer and presumably all the ^{137}Cs. In the lower slope positions tillage depths, and consequently sampling, were generally shallower. In addition, the depth of Ap exceeded the depth of tillage. As stated above, the accuracy of the ^{137}Cs measurements depends on the assumption that the entire depth of soil enriched with ^{137}Cs was sampled, presumably the depth of the Ap horizon. This may also have contributed to underestimation of soil accumulation in the lower slope positions and possibly apparent soil loss where there was actually soil accumulation.

The end points of the transect/profile were excluded from the validation because it was impossible to calculate ö at these points and è beyond these points using the forward and backward difference calculations used in the model.

The relationship between the predicted and estimated rates of soil accumulation was (see Tables 8 and 9 and Figures 16 and 17):

$$\mathbf{P = 1.905 + 0.487 * E \quad (r^2 = 0.328)}$$

When estimates of variable field soil bulk density and tillage depth based on landscape position were used the relationship was:

$$P = 1.656 + 0.405 * E \quad (r^2 = 0.284)$$

When estimates of constant field soil bulk density of 1300 kg m^{-3} and tillage depth 0.178 m were used the relation ship was:

$$P = 1.266 + 0.411 * E \quad (r^2 = 0.170)$$

When estimates of constant field soil bulk density of 1627 kg m^{-3} and tillage depth 0.230 m were used the relationship was:

$$P = 1.266 + 0.655 * E \quad (r^2 = 0.170)$$

Since a detailed elevation had been conducted at the field site, the slope gradient and curvature was calculated for the immediate area (over a 4 m slope length) of each plot. These values were also used to predict translocation and these results were compared to the estimates:

$$P = 2.538 + 0.676 * E \ (r^2 = 0.261)$$

It is obvious from the data that the estimated soil loss and the predicted are more closely related than the regression analysis would indicate. The soil loss peaks appear slightly out of phase. One possible cause for this is the effect of the ridge's asymmetry on factors other than slope gradient and curvature that also effect tillage translocation and tillage erosion such as tillage depth and speed. To test this idea the data points were shifted one position so that the soil loss peaks were aligned and the regression analysis was conducted again. For the adjusted data:

$$P = 4.325 + 0.835 * E \quad (r^2 = 0.805)$$

This highlights the need for more comprehensive data collection, particularly the inclusion of tillage depth, during tillage translocation experiments. This also has serious implications on the calibration, raising the question: would the inclusion of tillage depth and speed have reduced the unexplained variability observed in the calibration procedure and improved the model's accuracy?

Figure 12: Topography of the Huron field site, elevations of transects 1 through 4, and their average.

Figure 13: Topography of the Brant field site and Huron field site.

Figure 14: Distribution of resident ^{137}Cs radioactivity at the Huron field site; a) transects 1 through 4, and their average; b) average of transects 1 and 2 (chisel plough), 3 and 4 (mouldboard plough), and 1 to 4.

Figure 15: Soil redistribution at the Huron field site. Estimates of soil accumulation rates estimated using: #1) measured plot averages for soil bulk density and maximum tillage depths (variable), #2) estimates of soil bulk density and tillage depth based on landscape position (variable), and #3) field averages for soil bulk density and tillage depth (1627 kg m^{-3}, 23.0 cm).

Figure 16: Landscape profile of estimated and predicted soil accumulation rates at the Huron field site - estimated using resident ^{137}Cs and predicted using the tillage erosion model.

Figure 17: Comparison of soil accumulation rates at the Huron field site predicted with the tillage erosion model and those estimated using resident ^{137}Cs radioactivity.

Table 8a: Predicted Soil Redistribution at the Huron County Field Site (Tillage Direction `1 to 10')

	Distance (m)	Elevation (m)	Slope Gradient w.r.t. Tillage Direction (%)		Slope Curvature (% m^{-1})	Predicted Net Tillage Translocation Output-Input (kg m^{-1} per tillage pass)			Predicted Rate of Soil Accumulation (kg m^{-2} per tillage pass)				Rate of Soil Accumulation‡ (cm per tillage sequence)
			Input	Output		Mouldboard Plough	Tandem Disc	Field Cultivator	Mouldboard Plough	Tandem Disc	Field Cultivator	Tillage Sequence †	
1	155.9	0.20		-0.9		33.8	23.9	29.6	-1.72	-1.22	-1.51	-5.66	-0.39
2	116.6	0.55	-0.9	-4.4	-0.10	-3.9	-3.9	-1.6	0.11	0.11	0.04	0.38	0.03
3	86.5	1.88	-4.4	-7.5	-0.18	-3.9	-3.7	-1.8	0.23	0.22	0.10	0.77	0.05
4	82.5	2.18	-7.5	-8.2	-0.06	-0.9	-0.8	-0.5	0.09	0.08	0.04	0.29	0.02
5	65.3	3.59	-8.2	-3.9	0.35	5.8	5.5	2.8	-0.47	-0.44	-0.23	-1.58	-0.09
6	57.7	3.89	-3.9	3.8	1.15	13.1	11.7	7.4	-1.96	-1.75	-1.10	-6.57	-0.36
7	51.9	3.67	3.8	11.4	0.94	12.0	10.9	6.5	-1.49	-1.35	-0.80	-4.99	-0.28
8	41.5	2.47	11.4	8.2	-0.21	-4.1	-3.9	-1.9	0.28	0.26	0.13	0.93	0.06
9	22.0	0.87	8.2	4.3	-0.22	-4.8	-4.6	-2.2	0.27	0.26	0.12	0.90	0.06
10	5.3	0.15	4.3			-38.7	-29.0	-31.2	4.62	3.47	3.72	15.28	1.05

† Conventional tillage sequence consisting of mouldboard plough, tandem disc (double pass), field cultivator (single pass).

Table 8b: Predicted Soil Redistribution at the Huron County Field Site (Opposite Tillage Direction `10 to 1')

	Distance (m)	Elevation (m)	Slope Gradient w.r.t. Tillage Direction (%)		Slope Curvature (% m^{-1})	Predicted Net Tillage Translocation Output-Input (kg m^{-1} per tillage pass)			Predicted Rate of Soil Accumulation (kg m^{-2} per tillage pass)				Rate of Soil Accumulation‡ (cm per tillage sequence)
			Input	Output		Mouldboard Plough	Tandem Disc	Field Cultivator	Mouldboard Plough	Tandem Disc	Field Cultivator	Tillage Sequence †	
1	155.9	0.20		-0.9		-35.4	-25.6	-30.1	1.81	1.31	1.53	5.95	0.41
2	116.6	0.55	-0.9	-4.4	-0.10	-3.9	-3.9	-1.6	0.11	0.11	0.04	0.38	0.03
3	86.5	1.88	-4.4	-7.5	-0.18	-3.9	-3.7	-1.8	0.23	0.22	0.10	0.77	0.05
4	82.5	2.18	-7.5	-8.2	-0.06	-0.9	-0.8	-0.5	0.09	0.08	0.04	0.29	0.02
5	65.3	3.59	-8.2	-3.9	0.35	5.8	5.5	2.8	-0.47	-0.44	-0.23	-1.58	-0.09
6	57.7	3.89	-3.9	3.8	1.15	13.1	11.7	7.4	-1.96	-1.75	-1.10	-6.57	-0.36
7	51.9	3.67	3.8	11.4	0.94	12.0	10.9	6.5	-1.49	-1.35	-0.80	-4.99	-0.28
8	41.5	2.47	11.4	8.2	-0.21	-4.1	-3.9	-1.9	0.28	0.26	0.13	0.93	0.06
9	22.0	0.87	8.2	4.3	-0.22	-4.8	-4.6	-2.2	0.27	0.26	0.12	0.90	0.06
10	5.3	0.15	4.3			30.5	20.5	28.5	-3.64	-2.45	-3.40	-11.94	-0.82

† Conventional tillage sequence consisting of mouldboard plough, tandem disc (double pass), field cultivator (single pass).

Table 9: Estimated and Predicted Soil Redistribution at the Huron County Field Site

	Distance (m)	Estimated Rate of Soil Accumulation (kg m^{-2} per tillage sequence)			Soil Bulk Density (kg m^{-3})	Tillage Depth (m)	Resident ^{137}Cs Radioactivity (Bq m^{-2})	Average Estimated Rate of Soil Accumulation‡ (kg m^{-2} yr^{-1})
		Direction \`1 to 10'	Direction \`10 to 1'	Annual Average†				
1	155.9	-5.66	5.95	0.15	1453	0.202	1862	5.1
2	116.6	0.38	0.38	0.38	1516	0.222	2209	-4.1
3	86.5	0.77	0.77	0.77	1615	0.249	1697	-5.3
4	82.5	0.29	0.29	0.29	1727	0.252	1935	-20.9
5	65.3	-1.58	-1.58	-1.58	1784	0.267	1461	-22.9
6	57.7	-6.57	-6.57	-6.57	1720	0.270	1500	-18.9
7	51.9	-4.99	-4.99	-4.99	1660	0.268	1266	-5.7
8	41.5	0.93	0.93	0.93	1617	0.255	1176	-0.0
9	22.0	0.90	0.90	0.90	1579	0.238	1861	8.7
10	5.3	15.28	-11.94	1.67	1595	0.230	1971	8.9

† Estimated annual rate of soil accumulation based average of two tillage sequences conducted in opposing directions.

‡ Estimated rate of soil accumulation calculated using Equation X given an initial radioactivity of resident ^{137}Cs of 2500 Bq m^{-2} in 1990.

Table 10: Cropping* History of Huron County Field Sites

Year	M. Lobb Field Site	G. Lobb Field Site	Year	M. Lobb Field Site	G. Lobb Field Site
1991	Soybeans	Soybeans	1975	Corn	Wheat
1990	Soybeans	Wheat	1974	Corn	White Beans
1989	Soybeans	Soybeans	1973	Grain	White Beans
1988	Corn	White Beans	1972	Grain	Hay
1987	Soybeans	Corn	1971	Corn	Hay
1986	Corn	Corn	1970	Corn	Hay
1985	Wheat	Wheat	1969	Wheat	Grain
1984	Soybeans	Soybeans	1968	White Beans	Grain
1983	Corn	Wheat	1967	Barley	Corn
1982	Corn	White Beans	1966	Grain	Corn
1981	Wheat	Corn	1965	Hay	Hay
1980	White Beans	Corn	1964	Hay	Hay
1979	White Beans	Wheat	1963	Hay	Hay
1978	Corn	White Beans	1962	Grain	Hay
1977	Corn	Wheat	1961	Grain	Grain
1976	White Beans	White Beans	1960	Grain	Grain

* All cropping practices conducted with conventional tillage.

SUMMARY

The proposed tillage erosion model provided a reasonably accurate prediction of soil redistribution at the Brant County field site when compared to that estimated using resident ^{137}Cs radioactivity. The tillage erosion model provided a relatively poor prediction of soil redistribution at the Huron County field site when compared to that estimated using resident ^{137}Cs radioactivity. There is some indication that the poor prediction for the Huron site was due in part to the model's simplicity (not able to predict the effect of curvature asymmetry on tillage erosion - a problem which would be greater at this site than the Brant site because of smaller scale of the ridge). Soil losses, based on the ^{137}Cs data, were situated on the convex upper slope landscape positions, but they were greater in severity on the shoulder slope position of the steeper of the ridge's two slope faces. Although the model correctly predicted the general pattern of soil losses and accumulations, the model underpredicted the magnitude, or severity, of soil losses at both field sites. Too few data of soil accumulation estimates were available to make a similar inference about soil accumulation. Several possible reasons for this underprediction of soil loss were identified: 1) the tillage implements and the tillage sequence used to predict the soil redistribution may have been less intensive than those responsible; 2) inaccuracies associated with the use of resident ^{137}Cs may have caused overestimation of soil redistribution (the problem associated with point measurements resulting in apparent losses on backslope positions, as well, the current level resident ^{137}Cs for a noneroded site may be much less than the assumed 2500 Bq m^{-2} in Huron County); 3) wind and water erosion may have caused soil redistribution in addition to that caused by tillage erosion (the redistribution pattern is inconsistent with that of soil erosion by overland water flow).

For a first attempt at modelling tillage erosion in complex landscapes the performance of the proposed model was considered very good. Clearly, there are limitations to the complexity and consequently predictive capabilities of the model due to the lack of experimental data for calibration procedures, particularly tillage depths. At the time the study was initiated, the number of parameters involved and the complexity of the relationships was not fully appreciated. This was exploratory research, and therefore presuming that a model could be developed on such a data set was very ambitious.

The fact that the proposed tillage erosion model predicts greater rates of soil loss on convex upper slope landscape positions where severe soil loss occurs, and soil accumulation in concave lower slope landscape positions where soil accumulation is observed, indicates that this model is more appropriate than water erosion models for predicting soil erosion in topographically complex landscapes. Consequently, it can be presumed that the proposed tillage erosion model is more appropriate than water erosion models for basing soil conservation decisions relating to soil degradation and soil productivity. Comprehensive soil erosion models including submodels for erosion by wind, water and tillage may provide the best prediction of soil redistribution in topographically complex landscapes.

Exercises that will be carried out as part of David Lobb's Ph.D. programme to further develop the tillage erosion model include:

< further examination of resident ^{137}Cs for estimating soil losses and accumulation in complex topography,
< further model validation using the resident ^{137}Cs data from the G. Lobb site in Huron County,
< further model validation using the resident ^{137}Cs data from the D. Lobb and M. Lobb Tillage-2000 sites, also in Huron County,
< examine the variability of, and the relationship between, tillage depth and tillage speed in complex landscapes,
< expand the model to include lateral translocation allowing the prediction of tillage translocation and tillage erosion in complex three dimensional landscapes. This procedure is simply the expansion of a three point model to a five point model - input and output translocation calculated in the forward and sideward directions.
< Research that needs to be conducted to further develop the tillage erosion model, through more extensive calibration, includes:
< tillage translocation experiments where tillage depth and tillage speed are quantified,
< lateral tillage translocation experiments,
< tillage translocation experiments on soils other than sandy loam.

REFERENCES

Butler, G.C. 1980. Radioactivity in the Canadian environment. NRCC No. 18134. Associate Committee on Scientific Criteria for Environmental Quality. National Research Council of Canada, Ottawa. pp. 69-73.

Crosson, L.S. 1972. Stereortho photos - soil landform relationships - soil classification. Ph.D. Thesis. Dept. Land Resource Science, Univ. of Guelph, Guelph, ON. p. 237.

de Jong, E., H. Villar, and J.R. Bettany. 1982. Estimates of soil erosion and deposition for some Saskatchewan soils. Can. J. Soil Science. 63: 607-617.

Kachanoski, R.G., R.D. Protz, and E.G. Gregorich. 1992. Management of Farm Field Variability: I. Quantification of Soil Loss in Complex Topography. SWEEP/TED report. Centre for Soil and Water Conservation. University of Guelph, Guelph, ON.

Kachanoski, R.G. 1987. Comparison of measured soil ^{137}-Cesium losses and erosion rates. Can. J. Soil Science. 67:199-203.

Kachanoski, R.G. and E. de Jong. 1984. Predicting the temporal relationship between ^{137}-Cesium and erosion rate. J. Environmental Quality. 13:301-304.

Lobb, D.A. 1990. Soil erosion processes on shoulder slope landscape positions. M.Sc. Thesis. Dept. Land Resource Science, University of Guelph, Guelph, ON. p. 390.

Lobb, D.A., R.G. Kachanoski, M.H. Miller. 1992a. Management of Farm Field Variability: II. Soil Erosion Processes on Shoulder Slope Landscape Positions. SWEEP/TED report. Centre for Soil and Water Conservation. University of Guelph, Guelph, ON.

Lobb, D.A., R.G. Kachanoski, M.H. Miller. 1992b. Soil Loss by Tillage Erosion: the Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by tillage. SWEEP/TED report. Centre for Soil and Water Conservation. University of Guelph, Guelph, ON.

Lobb, D.A., R.G. Kachanoski, M.H. Miller. 1993. Soil loss by tillage erosion on shoulder slopelandscape positions. J. Soil and Tillage Research. Submitted for publication.

APPENDIX A

Research Proposal Submitted to Agriculture Canada

June, 1990

RESEARCH PROPOSAL

1. **PROJECT TITLE:** The relationship between landscape position, tillage practices, and soil loss: model development

2. **NAME & ADDRESS OF ESTABLISHMENT:**

Centre for Soil and Water Conservation
Richards Building
University of Guelph
Guelph, Ontario N1G 2W1

3. **TELEPHONE NUMBER:** (519) 824-4120 Ext. 2484

4. **ICAR REGISTRATION NUMBER OF ESTABLISHMENT:** 30601

5. **CONTACT PERSON:** David A. Lobb

6. **PERSONNEL:**

		TIME COMMITMENT		
a)	Principal Researcher	Year 1	Year 2	Year 3
	Dr. R. Gary Kachanoski Dept. of Land Resource Science	0.05	0.05	0.05
b)	Graduate Student David A. Lobb Dept. of Land Resource Science	1.00	1.00	0.58

7. **PLANNED PROJECT START DATE:** September 1, 1990

8. **PLANNED PROJECT TERMINATION DATE:** March 31, 1993

9. **BUDGET SUMMARY:**

	Year 1	Year 2	Year 3	Total
Personnel	15,000	15,000	8,750	38,750
Overhead	9,750	9,750	5,688	25,188
Travel Expenses	2,000	2,000	500	2,500
Overhead	40	40	10	50
Computer Time and Supplies	3,000	3,000	2,000	10,000
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TOTAL	29,790	29,790	16,948	76,528

BACKGROUND

The prediction of soil loss has become a major initiative of current agricultural and environmental research. Intensive research by the United States Department of Agriculture is currently taking place to develop the Water Erosion Prediction Program (WEPP). WEPP is a process based model which predicts the movement of soil and water in complex topography and through major gully and rill areas. Agriculture Canada, as part of the National Soil Conservation Programme, is planning to evaluate WEPP under Canadian environmental conditions. This initiative has been taken in an attempt to sustain soil productivity, and improve water quality by reducing sediment loads in watercourses.

Severe soil loss on agricultural land in Southern Ontario occurs predominately on divergent upperslope landscape positions. Visual evidence of severe soil loss on upper slope positions can be found throughout the upland regions of Southern Ontario in the form of exposed subsoil and undercut fencerows on the divergent areas of ridges and knolls. It has been estimated that this form of severe soil loss currently affects 10 % to 20 % of the agricultural land area in the upland regions of Southern Ontario (Battison et. al., 1987). The amount of area affected by this form of severe soil loss within a farm field varies depending upon the scale of topographic complexity.

Battison et. al. (1987) estimated rates of soil loss in excess of 150 t ha^{-1} yr^{-1} on shoulder slope positions within several farm fields in Waterloo County. Topographic features termed shoulder slopes are the transitional convex areas between the slope-crest and the linear slope-face. These rates have been confirmed by resident cesium-137 measurements (Kachanoski and Miller pers. comm., 1988). Crop yield reductions of 40 % to 60 % were associated with the soil loss on these severely eroded shoulder slope positions (Battison et al., 1987). Similar rates of soil loss have been measured on shoulder slope positions in a Brant County farm field using resident cesium-137 measurements (Kachanoski and Gregorich, 1990).

The soil loss rates cited above are approximately ten times greater than any measured rate of wind or water induced soil erosion occurring on upper slope positions in Southern Ontario and several times greater than the greatest estimate of soil loss predicted by the Universal Soil Loss Equation (USLE), the Revised USLE, or any other soil loss prediction models currently available. All current models are based on either wind or water induced soil erosion processes. It may be concluded that the erosion processes occurring on divergent upper slope positions are not induced by wind or water.

It has been demonstrated that a single cycle of conventional tillage on moderate shoulder slopes can translocate soil over 200 cm when tillage is conducted in the upslope direction and over 300 cm when tillage is conducted in the downslope direction (Lobb et. al., 1990). In the preliminary analysis of the data, the net soil loss resulting from differential upslope-downslope soil translocation by a single cycle of conventional tillage on moderate shoulder slopes was found to be approximately 100 t ha^{-1} yr^{-1} when soil is tilled upslope equally as often as downslope (Lobb et. al., 1990). In reality tillage patterns result in some portions of the field being tilled in one direction only. Under these conditions soil losses could exceed 200 t ha^{-1} yr^{-1} on some areas of a field.

The aforementioned study by Lobb et. al. (1990) was conducted on three shoulder slope positions of sandy loam soil texture, located in a Brant County farm field near Burford.

Paired plots labelled with ^{137}Cs were utilized to compare soil translocation by upslope tillage and downslope tillage. The conventional tillage system consisted of one fall primary tillage operation: mouldboard plough equipped with four 16" high speed bottoms; and three spring secondary tillage operations: tandem disc, 10' cutting width, equipped with 14" diameter disc blades at 7" spacing (double pass), and C-tine cultivator, 10' working width, equipped with narrow 4" sweeps at 7" spacing, and a rear-mounted Buster-bar harrow (single pass). Average ploughing depth was 17 cm and the depth of secondary tillage operations was approximately 10 cm. Primary tillage operations were conducted with a 70 horsepower tractor and secondary tillage operations were conducted with a 67 horsepower tractor. Primary tillage operations were conducted when there was a 5 cm to 10 cm thick layer of frozen ground which is suspected of impeding soil translocation. Under these conditions tractor speed was reduced to 2 mph to 3 mph, one half of the recommended speed. All subsequent tillage operations were conducted at 2 mph to 3 mph to maintain consistency. The consequence of this reduction in speed is a reduction in soil translocation. The tillage conducted in this study would be considered minimal by conventional standards and, therefore, the estimate of 100 t ha^{-1} yr^{-1} soil loss under a conventional tillage system should be considered conservative.

This study was replicated on five shoulder slope positions of clay loam soil texture, located in a Middlesex County farm field near Lucan. Similar rates of soil loss resulting from tillage were observed.

The conclusion of the study by Lobb et. al. (1990) is that tillage erosion probably dominates the soil erosion processes occurring on divergent upper slope positions of the landscape and that tillage erosion is probably responsible for the soil losses and crop yield reductions observed on divergent upper slope positions. This conclusion is based on the fact that the rate of soil loss measured in this study accounts for most of the observed soil losses from shoulder slope positions.

Apart from the severe loss of soil on upper slope positions, and the associated reduction in soil productivity, there is another major consequence of soil translocation by tillage. Soil lost from divergent upper slope positions by mechanically induced soil erosion processes is translocated to convergent lower slope positions where concentrated water flow occurs. Tillage, by delivering soil to areas of concentrated water flow, such as rills, results in the increased transport of soil from the field into the local watercourse. This process is suspected to dominate any inter-rill to rill soil movement. The WEPP model is based on the process of inter-rill to rill soil movement by water.

If soil movement is completely dominated by tillage erosion, no soil will be lost from the boundaries of the field. It will simply be redistributed within the field in a levelling process. Kachanoski and Gregorich (1990) have shown, using resident cesium-137 measurements, that within a Brant County farm field experiencing severe soil loss on divergent upper slope positions over a period of fifteen years, no significant amount of soil was lost from the field. Soil losses were accounted for by soil deposition in lower slope positions.

Furthermore, as subsoil on the upper slope positions becomes exposed the soil translocated downslope becomes increasingly erodible and less productive. Eventually, unproductive subsoil from upper slope positions will cover the productive topsoil of the lower slope positions.

The evaluation, modification, or development of any model, such as WEPP, to predict total soil losses from agricultural land, for the purpose of sustaining soil productivity or reducing sediment loads in watercourses, must consider tillage erosion as a significant soil erosion processes.

PROPOSED STUDY

The purpose of this study is to develop a working model based on the process of tillage erosion to be used in conjunction with existing wind and water process based models, such as WEPP, to predict soil losses from agricultural land. This model will demonstrate the relationship between landscape position, tillage practices, and soil loss.

A stochastic transfer function approach will be taken to modelling the translocation of soil by tillage. The movement of a soil particle will be described by a distance travel probability density function f_D (x). If the original distribution of soil (or tracer) is given by M_o (x), where x = horizontal spatial distance and M (x) = specific soil mass (kg m^{-2}) in the till layer, then the distribution of soil mass after tillage, M_T (x), can be given by the convolution integral,

$$\mathbf{M_T (x) = \quad M_o (x-x') f_D (x) dx'}$$

The model will need to be expanded to include the dependence of f_D (x) on spatial location as a function of the slope gradient. Soil translocation by tillage should be related to slope gradient alone, not slope gradient and slope length as is the case with water based processes such as WEPP. Soil loss resulting from tillage translocation of soil, therefore, should is related to the change in slope or topographic curvature. Thus, the dependence of f_D (x) on slope gradient needs to be determined.

If the original distribution of specific soil mass, M_o (x), was approximately a delta function (x) having the properties,

$$\mathbf{(x) = 1, x = x'}$$
$$\mathbf{(x) = 0, x = x'}$$

then the solution of the convolution integral (Equation [1])

$$\mathbf{M_T (x) = \quad (x-x') f_D (x)dx'}$$

is given by

$$\mathbf{M_T (x) = f_D (x)}$$

Thus, the form of the distance travel probability density function can be obtained from the distribution of a banded soil tracer after tillage events have occurred.

The f_D (x) will be determined for various tillage implements on various slope and landscape combinations as described in the proposed Soil and Water Environmental Enhancement Programme (SWEEP) study (see Appendix A). By comparing upslope tillage and downslope tillage f_D (x) for given tillage implements and given slope gradients, net soil loss for different tillage combinations and tillage directions can be modelled.

The model will be calibrated with the data from the existing data base of the SWEEP study by Lobb et. al. (1990) and data from a second data base of the proposed SWEEP study (see Appendix A). The accuracy of the model will be tested on the Tillage-2000 data base of soil loss as indicated by resident cesium-137. The Tillage-2000 study includes comprehensive information on topography, tillage systems, soil loss, and crop yield variability.

This project is being initiated with the understanding that it will be a joint effort with the proposed SWEEP study (Soil Loss by Tillage Erosion: The Effects of Tillage Implement, Slope Gradient, and Tillage Direction on Soil Translocation by Tillage) and the monies will largely fund a graduate student stipend to carry out the analysis of the proposed SWEEP study, to complete the theoretical development, and construct and validate the tillage-topography-soil loss model. The tillage-topography-soil loss model is viewed as a necessary addition to the current soil loss prediction models and could be used in conjunction with models, such as WEPP, to predict total soil loss.

REFERENCES

Battison, L.A., M.H. Miller and I.J. Shelton. 1987. Soil erosion and corn yields in Ontario. 1Field evaluation. Can. J. Soil Sci. 67:731-745.

Kachanoski, R.G and E.G. Gregorich. 1990. Management of farm field variability. 1989-90 Technical Evaluation and Development (TED) Annual Report.

Kachanoski, R.G. and M.H. Miller. 1988. Personal communication.

Lobb, D.A., R.G. Kachanoski and M.H. Miller. 1990. Severe soil loss on shoulder slopes: causes and control. 1989-90 Technical Evaluation and Development (TED) Annual Report.

DELIVERABLES

Upon completion of this study a comprehensive report will be produced by the University of Guelph for Agriculture Canada as part of the National Soil Conservation Programme, including: a comprehensive description of the processes involved, data confirming the existence of these processes, and a working model demonstrating the relationship between landscape position, tillage system, and soil loss. A supplementary report will also be produced for the funding source including full documentation of expenditures incurred by the University of Guelph in the course of this study.

DETAILED WORK SCHEDULE

Sep-Dec 1990 - course work, data analysis, theoretical development

Jan-Apr 1991 - course work, data analysis, theoretical development

May-Aug 1991 - comprehensive exams, theoretical development

Sep-Dec 1991 - model construction

Jan-Apr 1992 - model construction

May-Aug 1992 - model validation

Sep-Dec 1992 - model validation

Jan-Mar 1993 - completion of final report

ESTIMATED COST

YEAR 1 - SEPTEMBER 1, 1990 TO AUGUST 31, 1991	
Personnel:	
- Principal Researcher (R.G. Kacahnoski)	0
- Graduate Student Stipend	15,000
- Overhead (**to be negotiated**, maximum @ 65%)	9,750
Computer Time and Computer Supplies:	
- Computer time, math coprocessor, disks, etc.	3,000
Travel Expenses:	
- Meetings and Conferences	2,000
- Overhead (@ 2 %)	40
YEAR 2 - SEPTEMBER 1, 1991 TO AUGUST 31, 1992	
Personnel:	
- Principal Researcher (R.G. Kacahnoski)	0
- Graduate Student Stipend	15,000
- Overhead (**to be negotiated**, maximum @ 65%)	9,750
Computer Time and Computer Supplies:	
- Computer time, paper, disks, etc.	3,000
Travel Expenses:	
- Meetings and Conferences	2,000
- Overhead @ 2 %	40
YEAR 3 - SEPTEMBER 1, 1992 TO MARCH 31, 1993	
Personnel:	
- Principal Researcher (R.G. Kachanoski)	0
- Graduate Student Stipend	8,750
- Overhead (**to be negotiated**, maximum @ 65%)	5,688
Computer Time and Computer Supplies:	
- Computer time, disks, paper etc.	2,000
Travel Expenses:	
- Meetings and Conferences	500
- Overhead @ 2 %	10
TOTAL COST	$ 76,528

APPENDIX B

Interm Summary Report Submitted to Agriculture Canada

February, 1993

The model devlopment will continue beyond March 31, 1993 without funding from Agriculture Canada. The model is currently undergoing calibration and validation. It was not anticipated that the project could be completed in the two year period in which funding was made available. Dr. R. Coote and Dr. W. Findlay, who were involved in the project proposal development, were aware of time constraints and the possibility that an unfunded extension would likely be required. It is expected that the model will be completed by March 31, 1994. A report summarizing the status of the project will be submitted to Dr. A. Hammill March 31, 1993. Below are some conceptual and physical aspects of the model in development.

David Lobb is currently employed as the Soil Conservation Specialist for the Eastern Canada Soil and Water Conservation Centre in Grand Falls New Brunswick. David's Ph.D. program will continue on a part-time basis. Both his advisory committee and the Centre have aggreed to this arrangement.

Tillage Translocation is defined as the displacement of soil by tillage resulting in the redistribution of soil. Displacement is a response to the forces acting on the soil during tillage: draught force applied through the tillage tools, gravity, and the internal resistance to displacement due to the cohesive and adhesive properties of the soil. The displacement and redistribution of each particle of soil constituting the tilled layer will depend on its position (vertical and lateral) within the tilled layer relative to the tillage tools as well as the conditions of, and the association with, the surrounding soil. The impulse applied to the soil varies across the cross-section of tillage (laterally and vertically). Consequently, the displacement of soil varies across the width of tillage and throughout the depth of tillage as a result of tillage tool shape and arrangement.

Tillage tools apply a continuous impulse to the mass of soil within the tilled layer. Translocation can be conceptualized as an instantaneous event at a discrete point within space and time. The quantity of soil translocated is the cummulative result of the instantaneous events during tillage.

Displacement and redistribution can be represented as a time or space dependent decay function. The following equation is the proposed model of the response to instantaneous impulse by tillage tools, i.e. the impulse response function or transfer function.

$$g_{(x)}\,'\,\frac{1}{\hat{o}}e^{\&x/\hat{o}}$$

Instantaneous impulse applied continuously over tillage path produces a continuous response. The following equation is the proposed model of the response to continuous impulse by tillage tools, i.e. the step response function or translocation function.

$$h_{(x)}\,'\,1\&e^{\&x/\hat{o}}$$

When expressed as a decay function the decay constant ôis equivalent to a shift, uniform in depth, of the till layer ë. Both ôand ë are assumed to be representative of the tillage width, unit width averages. Translocation functions should represent both forward and backward translocation relative to the direction of tillage.

Tillage Erosion is defined as the variable redistribution of soil through tillage translocation resulting in net losses and net accumulations of soil along the path of tillage transecting a landscape. The action of tillage is dynamic in that the impulse applied to the soil varies in time and space in response to the spatial complexity of the landscape. Net translocation (kg m^{-1} tillage width per tillage pass) is the measure of variable translocation and redistribution of the soil by tillage at a position in the path of tillage, which translates into soil loss (kg m^{-1} tillage width m^{-1} length over which the soil is lost per tillage pass). Tillage erosion occurs when the magnitude of translocation changes in response to either a change in tillage erosivity or landscape erodibility.

The definition of tillage erosion was modified from previous documents to include the potential for the redistribution of soil, defined by its mass, O.M.C., ^{137}Cs, etc., even where topographic or tillage parameters are constant, i.e. the variability of these properties will result in their redistribution and apparent loss and accumulation under certain conditions.

The redistribution of soil within the landscape is modelled as a simple input/output system using estimated grid point values for soil and tillage parameters, and forward, backward and central differences for topographic parameters.

Tillage Erosivity is defined as the potential for tillage events to erode soil within a landscape. Tillage erosivity is a function of several physical and human parameters, including: tillage tool shape and arrangement within a tillage implement, tillage implement length and width, tractor-implement match, tillage depth and tillage ground speed, and tillage operator response to varying landscape conditions. The tillage parameters are controlled by selection and varied by the operator.

Landscape Erodibility is defined as the potential for the soil within the landscape to be eroded by tillage events. Landscape erodibility is a function of the topographic and soil parameters, including: slope gradient and curvature, and field soil bulk density, soil moisture content, and the ability of the soil to resist displacement and translocation (internal friction due to cohesion and adhesion). The landscape parameters are uncontrolled but evolve through erosion.

Calibration is being conducted with two data sets, Management of Farm Field Variability II. Soil Loss on Shoulder Slope Landscape Positions (SWEEP), and Tillage Translocation (SWEEP). The extent of calibration will be limited by the amount of data in these two reports.

Validation will be conducted using the data set from Management of Farm Field Variability I. Quantification of Soil Loss in Complex Topography (SWEEP).

One significant issue that has been raised during the model development, which affects any validation of erosion models (i.e. WEPP), is that resident ^{137}Cs is not an accurate indicator of soil redistribution in complex topography where the rate of redistribution is high and/or when the duration is long.