Tillage is a driving force of soil movement in cultivated fields. Soil constituents, together with the mass of soil, are redistributed across landscapes by tillage. The pattern of tillage-induced soil constituent redistribution is determined by the pattern of tillage erosion (tillage-induced soil mass loss or gain) and the dispersivity of translocation. In this study, we used a convoluting procedure and developed a Tillage Translocation Model (TillTM) to simulate the tillage translocation process and to demonstrate tillage-induced soil mass and soil organic carbon (OC) (as an example of soil constituents) redistributions across four hypothetical landscapes subjected to different tillage patterns (directions) and over different lengths of tillage period. We determined that the local tillage-erosion rate is mainly dependent on topography and that the effects of tillage pattern and the length of tillage period are relatively minor. The redistribution of OC content in the till layer is mainly determined by the number, location, and size of soil loss positions in the landscape, as well as the soil loss rates at these positions. Net loss of OC content occurs in the till layer and this loss increases with time. In contrast, an increase of OC content in the sublayer occurs at soil accumulation positions. The model was validated against field data collected at a site near Cyrus, MN. The patterns of OC and inorganic C redistribution can be adequately estimated by TillTM.

There are discrepancies, however, between the model-estimated values and the field measurements due to the limitations and uncertainties associated with the model. The results clearly showed that tillage translocation causes the vertical redistribution of soil constituents across the landscape, which implies that tillage translocation is one of the driving forces behind the spatial variability of soil properties and properties that impact biophysical processes.

Studies of tillage translocation and tillage erosion have been focused on the redistribution of soil mass. A diffusion model, proposed by Lindstrom et al. (1990), has been used by researchers worldwide to describe tillage translocation in different tillage systems (e.g., Govers et al., 1994; Quine et al., 1997; Lobb and Kachanoski, 1999b). Vertical mixture of soil from different soil horizons induced by tillage is referred to as the mixing effect. To investigate the redistribution of soil constituents, both the redistribution of soil mass and the mixing effect must be taken into account.

In further studies, Van Oost et al. (2003a,b) extended this model to two dimensions, which accounts for both forward and lateral tillage translocation. They concluded that the redistribution of soil mass and soil constituents has important implications for the understanding of the variation in soil properties within landscapes. It has been recognized that tillage erosion is a major cause of soil mass redistribution in cultivated landscapes (Govers et al., 1999). During tillage, soil constituents are translocated together with the soil mass. The redistribution of soil constituents is affected not only by the redistribution of soil mass but also by the mixing of subsoil into the till layer. For example, on convex positions, due to tillage-induced soil loss, organic-poor subsoil is exposed and brought up into the till layer, which results in the decrease (or dilution) of soil organic C (OC) content in the till layer (Papierink et al., 2005; Li et al., 2007b). During subsequent tillage, the OC-diluted soil is translocated to farther distances and eventually will propagate across the landscape and will cause a decrease in OC content in the till layer across the entire landscape, even in concave positions, where soil mass has accumulated (Lobb and Kachanoski, 1999b). Similarly, in landscapes with high-carbonate parent materials, tillage can cause an increase in soil inorganic carbon (IC) in the till layer due to the transfer of carbonate-rich subsoil into the till layer (De Alba et al., 2004). This vertical mixture of soil from different soil horizons induced by tillage is referred to as the mixing effect. To investigate the redistribution of soil constituents, both the redistribution of soil mass and the mixing effect must be taken into account.

Studies of tillage translocation and tillage erosion have been focused on the redistribution of soil mass. A diffusion model, proposed by Lindstrom et al. (1990), has been used by researchers worldwide to describe tillage translocation in different tillage systems (e.g., Govers et al., 1994; Quine et al., 1997; Lobb and Kachanoski, 1999a; Li et al., 2007b). In the diffusion models, the intensity of tillage translocation is generally characterized by the tillage transport coefficient(s) but no information is provided on the transfer of surface soil and subsoil. Kachanoski and de Jong (1984), however, suggested the possible effect of vertical mixture due to tillage translocation. Lobb (1997) demonstrated the impact of the dispersion of translocated soil and the mixing effect on the redistribution of 137Cs. Lobb and Kachanoski (1999b) suggested the use of an exponential function to simulate tillage translocation. Van Oost et al. (2000) proposed the use of a convoluting procedure to simulate the translocation process and established a model to predict soil constituent redistributions. In further studies, Van Oost et al. (2003a,b) extended this model to two dimensions, which accounts for both forward and lateral tillage translocation. They concluded that the
Tillage Translocation Simulation

We propose to improve on these preceding studies by further investigating the redistribution of soil mass and soil constituents under the context of different topographic features, tillage patterns (directions), and lengths of the tillage period. Unlike flat landscapes, topographically complex landscapes usually include isolated convexities so that there are areas of tillage-induced soil loss and, therefore, more sources of subsoil transferring into the till layer. The tillage pattern and the length of the tillage period can also affect the redistribution of soil mass and soil constituents. For example, when there is a predominant tillage direction, over the long term, continuous soil output from the starting boundary can result in the mixing of subsoil into the till layer in the starting-boundary area. This mixed soil (including the subsoil material) will be continuously spread out to the rest of the landscape with time.

The objectives of this study were: (i) to examine tillage-induced redistribution of OC (as an example of soil constituents) and soil mass across landscapes with different topographic features, in particular, across topographically complex landscapes; (ii) to investigate the effects of tillage patterns (directions) and the length of the tillage period on tillage-induced redistribution of OC and soil mass; (iii) to compare the differences and similarities between the redistribution of soil constituents and soil mass; and (iv) to validate and demonstrate the use of the TillTM.

MATERIALS AND METHODS
Tillage Translocation Simulation

A convoluting procedure was used in this study to simulate tillage translocation. Considering the landscape to be a series of adjacent sections, a given section receives soil translocated from its preceding sections (Fig. 1a). Soil in this given section is translocated into subsequent sections as well. The mass of soil in this given section after one tillage operation is the summation of all the soil translocated from its preceding sections plus the soil in this given section that has not been translocated elsewhere. The process can be described using a continuous form function as

$$S_a(x_0) = \int_0^{x_0} S_b(x) \cdot PD_x(x_0) \, dx$$  \hspace{1cm} [1]

where $x_0$ and $x$ are the distances from the original point (m) and $x < x_0$, $S_a(x_0)$ is the mass of soil per meter width at $x_0$ after a tillage operation (kg m$^{-1}$), $S_b(x)$ is the mass of soil per meter width at $x$ before a tillage operation, which is a constant when tillage depth and soil bulk density are considered to be uniform across the landscape (kg m$^{-1}$), and $PD_x(x_0)$ is the probability density of soil translocated from $x$ to $x_0$ (kg kg$^{-1}$ m$^{-1}$).

The translocation probability density, $PD_x(x_0)$, was simulated using an exponential function (Lobb and Kachanoski, 1999b):

$$PD_x(x_0) = \frac{1}{d_x} \exp \left( -\frac{x - x_0}{d_x} \right) \quad 0 \leq x_0 - x < \infty$$  \hspace{1cm} [2]

where $d_x$ is the mean soil translocation distance at $x$ (m).

Equations [1] and [2] were converted into discrete numeric forms as

$$S_a(x_0') = \sum_{x=x_0+1}^{x_0'} S_b(x) \cdot P_x(x_0')$$  \hspace{1cm} [3]

where $x_0'$ and $x'$ are the distances from the original point to the center of the sections (m), $P_x(x_0')$ is the probability of soil translocated from the section centralized at $x'$ to the section centralized at $x_0'$ (kg kg$^{-1}$ m$^{-1}$), $d_x$ is the mean translocation distance of soil in the section centered at $x'$ (m), and $I$ is the data interval (m).

The mean translocation distance ($d_x$) in Eq. [4] determines the shape of the soil distribution curve, i.e., how much soil is translocated to which distance. In mathematical terms, $d_x$ is the expected value (mean) of the distribution function, and indicates the average distance of the soil being translocated. The variation of the distribution function, which is an indicator of the dispersion of the translocated soil, is $d_x^2$. The value of $d_x^2$ varies across the landscape. Several factors contribute to this variation. Previous studies have proven that, for a given tillage operation, the value of $d_x$ is mainly determined by topographic features, i.e., slope gradient and slope curvature, at location $x'$ (e.g., Lindstrom et al., 1992; Lobb et al., 1999; Li et al., 2007a). A linear function has been commonly used to calculate $d_x$:

$$d_x = A + B \theta_x + C \varphi_x$$  \hspace{1cm} [5]
where $A$ is tillage translocation distance on level land (m), $B$ is additional tillage translocation due to the effect of slope gradient (m %$^{-1}$), $C_x$ is slope gradient at $x$ (%), $D$ is additional tillage translocation due to the effect of slope curvature (m$^2$ %$^{-1}$), and $Q_{xz}$ is slope curvature at $x$ (% m$^{-2}$).

The values of $A$, $B$, and $C_x$ characterize the dispersivity and erosivity of the tillage implements (Li et al., 2007a).

They are determined by implement type, tillage speed, tillage depth, and various soil properties (Lobb and Kachanoski, 1999a). For a certain tillage implement or tillage sequence, the values of $A$, $B$, and $C_x$ are calibrated with field tillage translocation experiments. In this study, $A$, $B$, and $C_x$ were assumed to equal 1 m, 0.02 m %$^{-1}$, and 0.04 m$^2$ %$^{-1}$, respectively, for one full sequence (1 yr), which represents a typical conventional tillage system (with moldboard plow) in corn (Zea mays L.) production in the northern North American Great Plains (Lindstrom et al., 1992; Lobb and Kachanoski, 1999a; Schumacher et al., 1999).

### Soil Mass and Soil Constituent Redistribution

Tillage erosion (soil mass loss or gain due to tillage) at a given location is calculated by the differences in the soil mass before and after a tillage operation:

$$
TE(x'_0) = S'_0(x'_0) - S_b(x'_0) = S'_0(x'_0) - \sum_{x_0}^{x'_0} P_{x'}(x'_0) \left[ \frac{x'_0 - x_0}{D_{x'}(x'_0)} \right] - 1 \tag{6}
$$

where $TE(x'_0)$ is net soil mass accumulation per meter width at $x'_0$ after the tillage operation, a negative value indicating net soil loss (kg m$^{-1}$).

Since $S'_0$ was considered to be a constant across the landscape, the variation of tillage erosion (TE) is solely determined by the integration term in Eq. (6). When the integration term is $<1$, soil loss occurs (Fig. 1b, total input < total output); when the integration term equals 1, input and output soil are balanced and no soil loss or soil accumulation occurs (Fig. 1b, total input = total output); when the integration term is $>1$, soil accumulation occurs (Fig. 1b, total input > total output).

A similar procedure was used to simulate soil constituent redistribution:

$$
C'_x(x'_0) = \sum_{x'_0}^{x'_0} \left[ C_b(x'_0) P_{\text{TillTM}}(x'_0) \right] \tag{7}
$$

where $C'_x(x'_0)$ is the amount of a soil constituent at location $x'_0$ after the tillage operation (kg m$^{-1}$), and $C_b(x'_0)$ is the amount of a soil constituent at location $x'_0$ before the tillage operation (kg m$^{-1}$). In contrast to $S'_0$, the amount of a soil constituent before the tillage operation, $C_b$, varies across the landscape and with time, so that both $C_b$ and $P_{\text{TillTM}}(x'_0)$ affect $C'_x$.

### The Tillage Translocation Model

A tillage translocation model (TillTM) was developed and written in Visual Basic 6.0 code. The TillTM is a two-dimensional model (in the horizontal and vertical dimensions). The inputs for the TillTM are the topography data and soil constituent concentrations as a function of depth at a series of data points along the tillage direction. Three layers are defined for the input data: the upper layer, the middle layer, and the bottom layer (Table 1). The model runs in loops. Each loop represents one tillage operation or one full sequence of tillage operations (e.g., 1 yr). In every loop, TillTM calculates tillage translocation at every data point. After the first loop, the depth of the upper layer is set as that of the till layer. The output from one loop is used as the input for the next loop.

The simulation of soil mass redistribution is based on Eq. [3–5]. A maximum translocation distance, $D_{\text{max}}$, is defined and Eq. [4] is modified to simulate soil translocation to this finite maximum distance:

$$
P_{\text{res}} = \frac{P_{\text{res}}}{(D_{\text{max}} + 1)} \tag{8}
$$

$$
P_{\text{adj}}(x'_0) = \left[ P_{\text{res}}(x'_0) + P_{\text{adj}}(x'_0) \right] \begin{cases} x'_0 - x'_0 \leq D_{\text{max}} \\ 0 & x'_0 - x'_0 > D_{\text{max}} \end{cases} \tag{9}
$$

Table 1. Summaries of the initial TillTM inputs for the hypothetical landscapes and the transect at the Cyrus site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth</th>
<th>Bulk density†</th>
<th>Organic C Proportion</th>
<th>Inorganic C Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>kg m$^{-3}$</td>
<td>%  kg m$^{-2}$</td>
<td>%  kg m$^{-2}$</td>
</tr>
<tr>
<td>Hypothetical landscapes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper layer†</td>
<td>0–0.20</td>
<td>1000</td>
<td>2.50</td>
<td>5.00</td>
</tr>
<tr>
<td>Middle layer</td>
<td>0.20–0.50</td>
<td>1200</td>
<td>0.25</td>
<td>0.90</td>
</tr>
<tr>
<td>Bottom layer</td>
<td>0.50–1.00+</td>
<td>1300</td>
<td>0.05</td>
<td>0.33$\ §$</td>
</tr>
<tr>
<td>Transect at Cyrus site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper layer†</td>
<td>0–0.25</td>
<td>1110</td>
<td>2.70</td>
<td>7.49</td>
</tr>
<tr>
<td>Middle layer</td>
<td>0.25–0.50</td>
<td>1230</td>
<td>0.70</td>
<td>2.15</td>
</tr>
<tr>
<td>Bottom layer</td>
<td>0.50–1.00+</td>
<td>1300</td>
<td>0.20</td>
<td>1.3$\ §$</td>
</tr>
</tbody>
</table>

† Bulk density of the fine earth portion.
§ Set at tillage depth in this study.

The simulation of soil constituent redistribution involves two steps. First, for a given data point, the resulting soil constituent content in the active till layer (Ap horizon) after tillage is calculated using Eq. [7]. Soil constituent concentration within this active till layer is assumed to be uniform after every tillage operation. Second, soil constituents are reassigned for the next tillage sequence according to the change in elevation (soil mass loss or gain). At soil loss positions, after tillage, there is a net output of soil mass from the active till layer (Fig. 1c). During the next tillage operation, tillage depth will exceed the depth of the original active till layer and the tillage implement will cut into the middle layer (normally, the B horizon). The top of the original middle layer becomes a part of the current till layer and, therefore, soil constituents in this part of the middle
layer are assigned to the current till layer and the depth of the middle layer decreases accordingly. The middle layer may eventually disappear at a soil loss position and in that case, the current till layer sits directly on the bottom layer, which is assumed to be the parent material layer (C horizon). In contrast, at soil accumulation positions, there is a net input of soil mass into the active till layer after tillage (Fig. 1d). During the next tillage operation, tillage implements will not be able to reach the bottom part of the original active till layer. Soil constituents in this untouched part of the active till layer are assigned to the middle layer.

Conditions at field boundaries affect the rest of the field. From a modeling standpoint, field boundaries are slope discontinuity points and behave as level topographic features where slope gradient and slope curvature equal zero. These field boundaries become flatter more quickly than other areas of the field due to tilling of the headlands (perpendicular to the dominant tillage direction). In TillTM, 5-m-width buffer zones are added to both ends (boundaries) of the landscapes. The initial elevations of the points in the buffer zones are made so that the slope gradient gradually changes to zero. After every tillage sequence, elevation is smoothed and soil constituent content is averaged in the buffer zones to simulate tilling the headlands. The buffer zone data were excluded from data analyses.

### Hypothetical Landscapes

Hypothetical elevation data were generated to represent four landscapes: a plane slope (PS, Fig. 2), a symmetric hill (SH, Fig. 3), an asymmetric hill (AH, Fig. 4), and an irregular hill (IH, Fig. 5). The PS is a straight line with a constant slope gradient of 10%. The SH has two asymmetric side slopes with the summit to the left of middle (50 m). The AH has two asymmetric side slopes (i.e., one side slope is shorter and steeper than the other side slope), with the summit to the left of middle (50 m). The IH represents a more complex landscape with both primary (coarse-scale) and secondary (medium-scale) topographic features (change of slope gradient and slope curvature on the order of ~100 m vs. on the order of ~10 m). The elevation of the IH was determined by adding a medium-scale elevation variation to the SH. Similar to the SH, the IH is symmetric in nature. All four hypothetical landscapes have the same span and data density, the same average absolute value of slope gradient, and approximately the same average slope curvature (Table 2). Furthermore, for the three hills (SH, AH, and IH), the percentages of convex and concave positions are also the same. Thus, the differences between the four landscapes lie in the different ranges and variations of both slope gradient and slope curvature. Other initial input data for the TillTM are summarized in Table 1.

Three tillage patterns were examined: forward-direction tillage, backward-direction tillage, and alternating-direction (forward–backward) tillage. In forward- and backward-direction tillage, tillage is conducted in the same direction every year, i.e., always forward or always backward. In the alternating-direction tillage, tillage is conducted in opposite directions at the same frequency, i.e., one forward-followed by one backward-direction tillage. For the two symmetric landscapes (SH and IH), the results of forward- and backward-direction tillage are the same; only forward-direction tillage was simulated. The model was run for 2, 10, and 50 loops, representing 2, 10, and 50 yr of tillage (referred to as short-, medium-, and long-term tillage, respectively).
Model Validation and Application—the Cyrus Site

The TillTM model was tested against data collected in a field located near the town of Cyrus, in west-central Minnesota. The study area (2.7 ha) is an undulating landscape and features a trough in the western part, a knoll in the middle and a slightly concave slope toward the eastern side of the field (Fig. 6). The field has been cultivated for approximately 100 yr and has been under conventional tillage (annual moldboard plow and tandem disk) for >40 yr. Tillage was conducted in west–east directions, alternately. Major crops grown in this field are corn, winter wheat (*Triticum aestivum* L.), and soybean (*Glycine max* (L.) Merr.). Most of the soils at this field site are of the Mollisol soil order in the U.S. Soil Taxonomy and are fine loamy, deep, and moderately to well drained. Soil parent material is carbonate-rich Wisconsinan-age glacial till. Previous studies suggested that both water and tillage erosion contribute to soil redistribution in this field but the major pattern of soil redistribution is dominated by tillage erosion (De Alba et al., 2004; Papiernik et al., 2005; Li et al., 2007b).

Along a transect across the midslope in the study area, 19 soil cores (7.6-cm diameter)
were collected to a depth of 1.40 to 1.50 m at approximately 10-m intervals in August 1999 (Fig. 2). The locations of the sample points were surveyed using a Trimble AgGPS-132 system with differential correction (Trimble Navigation, Sunnyvale, CA). Soil samples were sectioned by genetic horizons and were then air dried and sieved through a 2-mm screen. The fine-earth portion (soil particles <2 mm in diameter) was subsampled for TC and IC analysis. Total C was determined by Dumas combustion and measured using a LECO 2000 CN analyzer (LECO Corporation, 2003). Inorganic C was determined using a pressure calcimeter and OC was determined by the difference between TC and IC (Wagner et al., 1998). Organic C and IC contents for horizons (with various depth ranges for different sample points) were weighted based on depth and were converted to an area (volume) basis as the mass of OC and IC within 0- to 0.25- and 0.25- to 1.00-m depths (representing the till layer and the sublayer, respectively) for a unit area. Soil bulk density was determined along the same transect under relatively dry conditions in August 2000. Soil cores (5.7-cm diameter) were collected to 76-cm depth and sectioned into 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 76-cm increments. The bulk density was estimated by dividing the mass of soil by the volume of soil (calculated from the diameter of the core and the sample depth). Samples were also taken at five landscape positions (summit to footslope) on an adjacent grassed

Table 2. Characteristics of the four hypothetical landscapes.

<table>
<thead>
<tr>
<th>Landscape</th>
<th>Mathematical function</th>
<th>Span</th>
<th>Data interval</th>
<th>Slope gradient†</th>
<th>Slope curvature‡</th>
<th>Convex§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane slope</td>
<td>linear</td>
<td>200</td>
<td>0.10</td>
<td>Avg. Max. Min.</td>
<td>Avg. Max. Min.</td>
<td>%</td>
</tr>
<tr>
<td>Symmetric hill</td>
<td>triangular</td>
<td>200</td>
<td>0.10</td>
<td>10.0 15.7 0.0</td>
<td>0.00 0.49 -0.49</td>
<td>50</td>
</tr>
<tr>
<td>Asymmetric hill</td>
<td>triangular</td>
<td>200</td>
<td>0.10</td>
<td>10.0 30.6 0.0</td>
<td>0.06 1.40 -1.84</td>
<td>50</td>
</tr>
<tr>
<td>Irregular hill</td>
<td>sum of two triangular</td>
<td>200</td>
<td>0.10</td>
<td>10.0 22.0 0.0</td>
<td>0.00 2.32 -2.36</td>
<td>50</td>
</tr>
</tbody>
</table>

† Absolute value of slope gradient.
‡ Positive for convex positions and negative for concave positions.
§ Percentage of convex positions.
Tillage-induced OC and IC redistributions along the transect during the past 100 yr were simulated using TillTM. The model inputs are summarized in Table 1. The surveyed (current) elevation data were used since the elevation data before the field was cleared for agriculture (i.e., 100 yr ago) were not available. A spline function was used to interpolate the elevation data to 0.1-m intervals. The initial OC and IC contents were assumed to be uniform across the transect and were calculated by averaging the OC and IC contents, respectively, of the samples taken at the mid-slope positions on the grassed hillslope. Soil bulk density (fine earth) was also assumed to be uniform across the transect and was determined for each layer by averaging those of the transect samples and the grassed hillslope samples. In addition, soil bulk density was assumed not subject to change with time. The tillage pattern in TillTM was set as alternating (representative of the actual tillage management at the site) and the A, B, and C values in Eq. [5] were set as for the simulations with the hypothetical landscapes. Since only the current elevation data were available, for the calculation of the soil mass redistribution across the landscape (tillage erosion rates), the model was run for two loops. The output tillage erosion rate, therefore, is an estimation of the current tillage erosion rates. For the calculation of OC and IC redistribution across the landscape, the model was run for 100 loops to represent the past 100 yr. No change was applied to the elevation as a result of ongoing tillage erosion in the OC and IC simulation, i.e., the current elevation data were used for all 100 loops. This was done because the current elevation is already smoother than it was 100 yr ago and including the feedback of tillage erosion on elevation will make the elevation further smoothed after every loop and, therefore, more different from that of the past. The output OC and IC contents were converted to an area (volume) basis as the mass of OC and IC within the 0- to 0.25-m (the till layer) and 0.25- to 1.00-m (the sublayer) depth for a unit area. The performance of TillTM was evaluated using the correlation coefficients between the field measurements and the model estimates.

To examine the profile distribution of soil constituents in detail, 2-cm depth increment samples were taken at three locations within the field (knoll, trough, and footslope, Fig. 6) and at one baseline location in an adjacent undisturbed site (native grassland). The knoll and the trough points were on the transect, located on the eastern part of the knoll and the bottom of the trough, respectively (Fig. 6). The footslope point was not on the transect but located near the southern field boundary. The baseline point was on a flat, uncultivated grassland and there was no evidence of water erosion or tillage erosion at this slope position. Soils at the knoll point belong to the Langhei series (Typic Eutrudpts), and at the trough, footslope, and baseline points, to the Svea series (Pachic Hapludolls) (Lindstrom et al., 2000).

At each of the three field locations, seven cores (7.6-cm diameter) were taken within a 1-m radius. The baseline samples were collected from five cores (5.2-cm diameter) within a 5-m radius. Samples from the same depth ranges of the multiple cores were mixed together, air dried, and sieved (2-mm screen). Soil bulk density was estimated by dividing the mass of the soil by the volume of the soil (calculated from the diameter of the core, number of cores, and the sample depth). The $^{137}$Cs radioactivity of these samples was detected at 662 keV using broad energy germanium gamma spectrometers (Canberra BE3830, Landscape Dynamics Laboratory, Univ. of Manitoba, Winnipeg, Canada) with counting time ranging from 4 to 12 h, providing a detection error <10% (Li et al., 2007b). Organic C was measured on samples after removal of IC (6 mol L$^{-1}$ HCl digestion) and was determined by dry combustion using a LECO TruSpec CNS analyzer (Nelson and Sommers, 1982).

**RESULTS AND DISCUSSION**

**The Hypothetical Landscapes**

The results of TillTM simulation for the four hypothetical landscapes are shown in Fig. 2 to 5. In these figures, the elevation charts show the initial elevation (0 yr). For each tillage pattern, there are three charts: the tillage erosion charts show the average tillage erosion rates of 0 to 2, 2 to 10, and 10 to 50 yr; and the till-layer OC and profile OC charts show the amount of OC within the depth of 0 to 0.20 m (the tillage depth) and 0 to 1.00 m, respectively, after the given years of tillage.

**Tillage Erosion**

Except for the boundary areas, the patterns of tillage erosion on all four hypothetical landscapes were primarily determined by topography. On the PS, nonboundary areas showed neither soil loss nor soil accumulation. This is because the slope gradient is uniform on the PS and, therefore, at a given location, the amount of output soil is exactly the same as the amount of input soil (Fig. 2). In the three other hypothetical landscapes (SH, AH, and IH), soil loss corresponded to convexities and soil accumulation corresponded to concavities. The tillage erosion rates (negative for soil loss and positive for soil accumulation) was negatively correlated with slope curvature (negative for concavities and positive for convexities), i.e., greater slope curvatures displayed greater soil loss (Fig. 3–5). This is clearly shown when comparing the tillage erosion pattern of the SH to that of the AH or IH. Specifically, with the AH (Fig. 4), tillage-induced soil loss was more isolated, i.e., the size of the soil loss area was narrower, and soil loss rates on the hilltop were greater than those with the SH (Fig. 3). These were due to the fact that the absolute values of slope curvature on the hilltop and on the steep sideslope for the AH were greater than those for the SH. For the IH, excluding the boundary areas, the local tillage erosion rate of the IH hypothetical landscape was mainly determined by the...
secondary (medium-scale) topographic features and was characterized by peak–valleys, i.e., soil loss on small convexities and soil accumulation on small concavities (Fig. 5). The primary (coarse-scale) topographic features, however, also affected the basic trend of tillage erosion, e.g., the highest local soil loss rate was found on the small convexities on the hilltop (Fig. 5).

Tillage pattern (direction) affected tillage erosion in the boundary areas. Under one-direction tillage (forward or backward), the general pattern was characterized by soil loss near the starting boundaries and soil accumulation near the end boundaries (referred to as the boundary effect). The boundary effect was intense under one-direction tillage but only affected a limited distance, typically about 10 m from the boundary after 50 yr of tillage (Fig. 2–5). Under alternating-direction tillage, the boundary effect was considerably less intense than under one-direction tillage because the forward and backward translocation canceled each other. In the nonboundary areas, the patterns and rates of tillage erosion under different tillage patterns were found to be similar. Overall, the impacts of tillage pattern on tillage erosion were considered to be relatively minor.

It is noteworthy that on the PS hypothetical landscape, even under alternating-direction tillage, noticeable soil loss occurred near the top (left boundary) and noticeable soil accumulation occurred near the bottom (right boundary) (Fig. 2). This is due to the fact that downslope tillage moves soil farther than upslope tillage and agrees well with field evidence that soil loss occurs on the downslope of the field boundaries and soil accumulation occurs on the upslope of the field boundaries (Govers et al., 1999).

Excluding the boundary areas, on the PS, SH, and AH hypothetical landscapes, tillage erosion rates were almost identical for different lengths of tillage period, indicating that the length of tillage period has no noticeable effect on tillage erosion rates for topographically simple landscapes (Fig. 2–4). With the IH hypothetical landscape, however, the peaks and valleys of the 2-yr curve had the highest amplitudes, those of the 50-yr curve had the lowest amplitudes, and those of the 10-yr curve were in between (Fig. 5). This is due to the feedback of tillage erosion on the topography. The ongoing tillage erosion planes off the small convexities and fills up the small concavities, i.e., the small convexities and concavities are gradually smoothed out. The smoothing of the topography, as a result of tillage erosion, caused the subsequent decrease in tillage erosion (both soil loss and soil accumulation) with time.

**Till-Layer Soil Organic Carbon**

Unlike tillage erosion, which was counted as a rate (the amount of soil mass lost or gained per year), till-layer OC was counted as the total amount of OC in the till layer. For all the simulated tillage scenarios, the till-layer OC content was lower than or equal to the initial OC level (Fig. 2–5). The decrease in till-layer OC was a result of OC dilution due to the mixing effect—the transfer of OC-poor subsoil into the till layer. The till-layer OC did not increase in soil accumulation locations because soil accumulation only increases the depth of the OC-rich horizon, not the concentration of OC in the till layer. The rate of till-layer OC loss and the size of the till-layer OC loss area were influenced by the number and size of soil loss locations where subsoil was transferred into the till layer, as well as by the dispersivity of translocation. Topography, tillage pattern (direction), and length of tillage period all affected the pattern and intensity of till-layer OC loss (Fig. 2–5).

The pattern of till-layer OC loss varied with time. The general trend was that the longer the tillage period, the more profound the till-layer OC loss and the larger the size of the till-layer OC loss area. In the short term (2 yr), no noticeable till-layer OC loss was found on any landscape; in the medium term (10 yr), till-layer OC loss occurred in the soil loss positions; and in the long term (50 yr), greater till-layer OC loss was observed even in locations of soil accumulation (Fig. 2–5) and, in some cases, across the entire landscape (e.g., on the IH, Fig. 5).

Till-layer OC redistribution was also affected by tillage pattern. Under one-direction tillage, intense till-layer OC loss occurred near the starting boundaries in the medium term (10 yr) and propagated much farther beyond the areas of soil loss to about 50 m in the long term (50 yr) (Fig. 2–5). This is because soil from the starting boundaries was redistributed to the rest of the landscape through consecutive tillage translocation. Under alternating-direction tillage, the till-layer OC loss in the boundary areas was much less intense than under one-directional tillage because the input and output of soil mass and, therefore, OC in the boundary areas were canceled out in forward- and backward-direction tillage.

Landscape topography, more specifically, the number and size of convexities and the slope curvature of these convexities, determined the pattern and rate of soil loss and, therefore, affected the pattern of till-layer OC redistribution. In the PS hypothetical landscape, other than the boundary areas, there was no noticeable till-layer OC loss. In the SH and AH hypothetical landscapes, the hilltop provided another source of OC-poor soil and till-layer OC loss in the hilltops started to show up in the medium term (Fig. 3–4). Till-layer OC loss on the IH (Fig. 5) was considerably more intense than that on the SH or AH (Fig. 3–4) because all the small convexities are sources of OC-poor soil. In the medium term, till-layer OC loss occurred on the small convexities and in the long term, the entire landscape showed till-layer OC loss (Fig. 5). This indicates that on a topographically complex landscape, till-layer OC depletion is more widespread.

**Profile Soil Organic Carbon**

The TillTM provides estimates of OC content in both the till layer and the sublayer (to the depth of 1.0 m in this case). Profile OC is reported to provide the overall budget of OC at a given location. Unlike the till-layer OC content, profile OC content might be greater than the initial level. For example, this could occur at soil accumulation positions where the OC-rich surface soil is buried under the till layer. Whether the profile OC content increases or decreases at a given soil accumulation position is determined by the balance between the decrease in OC content in the till layer and the increase on OC content in the sublayer.

For all four hypothetical landscapes, under alternating-direction tillage, the patterns of profile OC agreed well with the respective patterns of tillage erosion: loss on convexities and gain on concavities (Fig. 2–5). On the IH, in particular, profile OC gain was found in the small concavities and increased with time, although soil accumulation rates in these small concavities decreased with time. This indicates that great amounts of OC are buried under the till layer in these small concavities. Under one-direction tillage, in addition to the topographic features, profile OC was also affected by tillage direction, espe-
cially in the boundary areas (Fig. 2–5). For example, on the PS, SH, and AH hypothetical landscapes, there were great profile OC losses near the starting boundaries and great profile OC gains near the end boundaries. The patterns of profile OC appeared to be similar to those of the till-layer OC (Fig. 2–4).

Due to continuous loss of soil mass, the loss of profile OC generally increased with time at soil loss positions. In contrast, the profile OC did not always increase at soil accumulation positions. For example, in the AH hypothetical landscape, under forward tillage, in the range of about 5 to 20 m, tillage caused soil accumulation (Fig. 4). In the medium term (10 yr), profile OC content was greater than the initial level in this area, but in the long term (50 yr), within the same area, profile OC content was lower than the initial level (Fig. 4). This is because the soil accumulation area is near the starting boundary, where till-layer OC concentration decreased with time. In the medium term, OC concentration in the accumulated soil was still close to the initial till-layer (upper layer) OC level (i.e., greater than the initial sublayer OC level), so that the overall OC budget in the profile was greater than the initial level. Soil accumulation did reduce the intensity of the profile

The Transect at the Cyrus Site

The transect runs from west to east on the upper midslope positions on the north–south slope (Fig. 6). Previous studies showed that water erosion along this transect has been minor and relatively uniform (Papiernik et al., 2005; Li et al., 2007b). TillTM-estimated tillage erosion featured two soil loss peaks (situated at about 70 and 100 m, respectively) and two soil accumulation peaks (situated at about 40 and 135 m, respectively) (Fig. 7). The soil loss peaks corresponded to the convex positions and the accumulation peaks corresponded to the concave positions. It is noteworthy that in the middle of the knoll (at about 90 m), the estimated local tillage erosion rate was close to zero. This is due to the relatively linear topography at this location.

For the OC, the patterns of field measurements and TillTM estimates were similar (Fig. 7). The correlation analyses for OC also showed that TillTM estimates were significantly correlated with field measurements (Table 3). In the till layer (0–0.25 m), both the field-measured and TillTM-estimated OC content were the lowest at locations around the two soil loss peaks. At the two soil accumulation peaks, the till-layer OC content was similar to that at the linear locations (Fig. 7). This indicates that the pattern of the till-layer OC is primarily determined by the position and size of the soil loss area in the field and is not greatly influenced by soil OC loss, however, as evidenced in Fig. 4 that in the long term, there is a peak of profile OC in the range of 5 to 20 m.
The two soil loss peaks, sublayer OC content was similar to
Eq. [5]) and with a simplified routine to simulate the decay and
**Significant at the 0.01 probability level.

* Signifi cant at the 0.05 probability level.

Table 3. Correlation coeffi cients between fi eld measure-
ments and TillTM estimates along a transect at the Cyrus
site (n = 19).

<table>
<thead>
<tr>
<th>Field measurements</th>
<th>TillTM estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Till-layer organic C (0–0.25 m)</td>
<td>0.65**</td>
</tr>
<tr>
<td>Sublayer organic C (0.25–1.00 m)</td>
<td>0.64**</td>
</tr>
<tr>
<td>Till-layer inorganic C (0–0.25 m)</td>
<td>0.58**</td>
</tr>
<tr>
<td>Sublayer inorganic C (0.25–1.00 m)</td>
<td>0.53*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

accumulation. This agreed with the conclusion drawn from the
simulations of the hypothetical landscapes. In contrast, for both
the fi eld-measured and TillTM-estimated sublayer (0.25–1.00 m)
OC curves, two peaks of sublayer OC content were present at the
same locations as those associated with the two soil accumulation
peaks, where OC-rich surface soil was buried under the till layer.
At the two soil loss peaks, the sublayer OC content was similar to
that at the linear locations. This indicates that the pattern of the
sublayer OC is primarily determined by the position and size of
soil accumulation areas, which also agreed with the conclusion
drawn from the simulations of the hypothetical landscapes.

The values of the TillTM-estimated till-layer OC were con-
siderably greater than those of the fi eld measurements. This sug-
gests that the initial till-layer OC level may be lower than the
input value (2.7%) or there is a net loss of OC in the till layer
due to water erosion, decomposition, or leaching (Papiernik
et al., 2007). Additional model simulations were conducted
to examine the model outputs with different settings of initial
input value (2.7%) but the pattern remained similar (data not shown). With
an optimized set of input parameters, a better match between
the model outputs and fi eld measurements could be made. This
suggests that had more accurate input data been available, the
accuracy of the OC estimates would have been enhanced.

For the IC, the correlation analyses showed that the TillTM
estimates were significantly correlated with the fi eld measure-
ments in both the till layer and sublayer (Table 3). The patterns
of the fi eld measurements and the TillTM estimates were also
similar in that till-layer IC content was the highest at the loca-
tions of the soil loss peaks, and sublayer IC content was the
lowest at the locations of the soil accumulation peaks (Fig. 7).
These were contrary to the respective patterns of OC in appear-
bance, but the processes were essentially the same: the exposed
subsoil at soil loss locations was OC poor but IC rich while the
buried surface soil at soil accumulation locations was OC rich
but IC poor. There were large discrepancies, however, between
the model estimates and the fi eld measurements. The fi eld mea-
surements appeared to have more extreme values. This suggests
that for IC redistribution, the effects of other processes could be
strong and the model uncertainties could be high.

Depth-Increment Profi les at the Cyrus Site

Both the knoll and the trough points are in the middle of the
north–south slope, with the local topography at the knoll point
being profi le and plan convex and the local topography at the
trough point being profi le linear and plan concave (Fig. 6). Previous
studies showed that water erosion causes soil loss at both of these
locations (Li et al., 2007b). In the trough, water-induced soil loss
is likely to be more intense than that on the knoll given that water
converges in the trough but diverges from the knoll (Fig. 6). Field
evidence also indicated that rills are well developed in the trough
but not on the knoll. The local topography determines that tillage
causes soil loss on the knoll but soil accumulation in the trough
(Fig. 6 and 7). At the footslope location, local topography is profi le
slightly concave and plan relatively linear. Water erosion may cause
soil loss or accumulation there. Tillage causes soil accumulation at
the footslope point but the intensity is likely to be lower than that
in the trough given that the concavity at the footslope point is less
than that at the trough point (Fig. 6). Overall, it was expected that
soil loss would occur at the knoll point and soil accumulation occur
at the trough and footslope points. These agreed with the TillTM-
estimated tillage erosion for the knoll and trough points (Table 4).
There was no TillTM estimation for the footslope point because this
point was not on the transect where the TillTM was applied.

At the baseline point, the 137Cs content continuously
decreased to negligible levels from the surface (except for the
fi rst point) to about 0.40 m (Fig. 8a). The basic pattern of 137Cs
at the three fi eld points (the knoll, trough, and footslope points)
was relatively uniform, with similar 137Cs contents within the
depth of 0.20 m, then decreasing sharply to negligible within
the depth range of about 0.20 to 0.50 m. This indicates that
tillage has mixed the 137Cs within the till layer and that the
tillage depth is around 0.20 to 0.30 m. In the 0- to 0.30-m
depth range, at any given depth, 137Cs content of the three
fi eld points followed the order: knoll < trough < footslope (Fig.
8a). If 137Cs redistribution were used as a direct measure of soil
mass redistribution, the loss or gain of 137Cs inventory (the
integrated profi le total 137Cs content within 0–1.00 m) at the
fi eld points, compared with that at the baseline point, can be
proportionally converted to gross soil erosion rates for about the
past 40 yr (including water, wind, and tillage erosion and their
interactions) as shown in Table 4.

![Fig. 8. (a) Profile 137Cs content and (b) profile soil organic carbon (OC) content, in 2-cm increments at four locations at the Cyrus site. The area between the curve and the two axes to a given depth indicates the total 137Cs or soil OC content in the profile to that depth.](image-url)
For OC, at the baseline point, OC content decreased exponentially with depth: quickly decreasing in 0 to 0.40 m and then slowly decreasing at greater depths (Fig. 8b). The OC content remained stable at about 0.12 kg m\(^{-2}\) (equivalent to about 0.35%) at depths >0.80 m. For all three field points, the integrated profile OC content to the depth of 1.00 m yielded 3.70, 12.99, and 11.58 kg m\(^{-2}\) for the knoll, trough, and footslope points, respectively (assuming that at the knoll point, the OC concentration in the 0.60–1.00-m layer equals the average OC concentration in the 0.50–0.60-m layer). These amounts were much lower than that of the baseline point (16.58 kg m\(^{-2}\)). The greatest differences in OC content between the field points and the baseline point were found at 0 to 0.30 m, indicating considerable OC loss within the till layer at all three field points. A reasonable explanation for this is that cultivation and cropping caused strong OC decomposition in the till layer. An additional explanation could be the exposure and translocation of OC-poor subsoil due to soil erosion, lowering the apparent OC in the topsoil relative to the baseline.

At the knoll point, the soil profile had consistently lower OC content with depth than the soil profiles at the other three points, suggesting greater OC loss at the knoll point. A sharp decrease in OC content at the knoll point was found at about 0.25 m. Above and below this depth, OC content remained relatively uniform. This indicates that tillage mixed the OC in the till layer and the tillage depth is around 0.25 m, which agreed with the \(^{137}\)Cs measurements. At the trough and footslope points, OC content also decreased with depth. No sharp decreases in OC content were found at 0.25 m; however, instead, relatively sharp decreases in OC content were found in the depth range of about 0.85 to 1.00 m and about 0.60 to 0.80 m for the trough and footslope points, respectively. In addition, within the depth range of about 0.45 to 0.95 m and about 0.35 to 0.70 m, at the trough and footslope points, respectively, OC content was considerably greater than that at the baseline point. These results suggest that OC-rich surface soil has been buried under the till layer at the trough and the footslope points due to soil accumulation. Within about the 0.55- to 1.00-m depth range, the OC content at the trough point was considerably greater than that at the footslope point, suggesting that soil accumulation at the trough point was more intense than at the footslope point. At the trough and footslope points, the depth where a sharp decrease in OC content occurs (roughly estimated at 0.85 and 0.60 m for the trough and footslope points, respectively) can be used as a measure of the intensity of soil accumulation. For instance, if the till-layer depth is estimated at 0.25 m, soil accumulated at the trough point during the past 100 yr can be estimated as 0.60 m (0.85 minus 0.25 m), or as an average rate of 76.8 Mg ha\(^{-1}\) yr\(^{-1}\). The soil accumulation rate at the footslope point was obtained similarly (Table 4).

With the available erosion estimates using the three different methods, except for the \(^{137}\)Cs estimate at the trough point, other estimates agreed with our expectations: soil loss at the knoll point and soil accumulation at the trough and the footslope point (Table 4). There were large discrepancies, however, in between. Part of these discrepancies could be explained by the underestimation and overestimation of the gross soil erosion using the TillTM and the OC-distribution method, respectively, and the uncertainties associated with the \(^{137}\)Cs method. The TillTM estimates the current tillage erosion rates. The ongoing tillage erosion may have caused the planing off of the knoll and resulted in the decrease in the tillage erosion rate with time (similar to what occurred on the small convexities in the IH hypothetical landscape, as shown in Fig. 5). It is reasonable to speculate that 100 yr ago, tillage erosion rates were greater than the current rate (absolute values). Furthermore, TillTM only takes into account tillage erosion and does not consider water and wind erosion. Overall, the TillTM probably has underestimated the gross soil erosion rates. The OC-distribution method is rough given that the determination of the depths (tillage depth and the depth where a sharp decrease in OC content occurs) was rough as well as that OC decomposition and crop growth may strongly affect the OC distribution in the profile. Furthermore, OC could be moved down the profile through leaching and deposited at deeper depths. Therefore, the OC-distribution method probably has overestimated the gross soil accumulation. Finally, the uncertainties associated with the \(^{137}\)Cs method may also contribute to the discrepancies. For example, \(^{137}\)Cs is primarily attached to fine particles and the selective removal of fine particles by water erosion may cause the overestimation of soil loss at the knoll and trough points. This overestimation was expected to be minor given that the estimated water erosion rates along the transect are relatively low (Papiernik et al., 2005; Li et al., 2007b).

The contradicting results for soil erosion at the trough point between the \(^{137}\)Cs method and the other two methods could not be explained, however, by the reasons listed above (Table 4). A possible explanation for the contradiction is the dilution of \(^{137}\)Cs due to tillage translocation. The trough point receives soil from nearby knolls (Fig. 6), where the till-layer \(^{137}\)Cs concentrations are low (Fig. 8a). The \(^{137}\)Cs method with a simple proportional model may not work here because the soil mass that is deposited in the trough contains relatively low amounts of \(^{137}\)Cs (i.e., the deposit soil is \(^{137}\)Cs diluted) or at least it will underestimate soil accumulation at the trough point. In contrast, the footslope point is farther from the knolls and receives soil from adjacent slopes that contain greater amounts of \(^{137}\)Cs in their profiles so that the influence of the dilution effect there is minor. This is also evidenced by the fact that in the till layer, the OC content at the footslope point was also slightly greater than that at the trough point (Fig. 8b). This explanation suggests that the dilution of \(^{137}\)Cs due to tillage translocation may be substantial.

### Table 4. Estimated erosion rates at the depth-increment profile points using different methods.

<table>
<thead>
<tr>
<th>Landscape position</th>
<th>TillTM erosion†</th>
<th>(^{137})Cs distribution</th>
<th>Organic C distribution</th>
<th>Erosion§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knoll</td>
<td>−35</td>
<td>Bq m(^{-2})</td>
<td>Mg ha(^{-1}) yr(^{-1})</td>
<td>857</td>
</tr>
<tr>
<td>Trough</td>
<td>60</td>
<td>1878</td>
<td>−12.5</td>
<td>0.65</td>
</tr>
<tr>
<td>Footslope</td>
<td>NA</td>
<td>2710</td>
<td>17.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Baseline</td>
<td>2224</td>
<td></td>
<td></td>
<td>44.8</td>
</tr>
</tbody>
</table>

† Current tillage erosion.

‡ Values were decay adjusted to 1 Jan. 2000 level.

§ Average gross soil erosion (including water, wind, and tillage erosion and their interactions) during the past ~40 yr.

¶ Average gross soil accumulation (including water, wind, and tillage erosion and their interactions) during the past ~100 yr.

# Method not applicable to this point.
at some locations on topographically complex landscapes and needs to be taken into account in the $^{137}$Cs technique.

The validation and application of TillTM clearly showed that tillage translocation causes the vertical redistribution of soil constituents across the landscape. Therefore, tillage translocation is considered to be one of the driving forces behind the spatial variability of soil properties and properties that impact biophysical processes such as crop production, nutrient cycling, greenhouse gas emission, and pesticide fate. For example, the burial of organic matter under the till layer (e.g., at the trough and footslope points) is a form of in-field C sequestration and the buried organic matter will have less value for crops. The incorporation of carbonates into the till layer (e.g., from the knoll point to the rest of the field) will affect soil properties such as pH and nutrient availability.

Model Limitations and Uncertainties

The TillTM developed in this study only simulates tillage-induced soil mass and soil constituent redistributions. Water and wind erosion were not considered in this model. Also, the TillTM is a two-dimensional (horizontal and vertical) model, while soil movement takes place in three dimensions in the field. Tillage, water, and wind erosion may all contribute to the total soil erosion observed in some landscapes. The interactions between different erosion processes also may contribute to total soil erosion (Li et al., 2007b). In addition, soil constituent redistribution is not only affected by soil movement, it is also affected by other chemical, physical, and biological processes. For example, decomposition and leaching may cause a net loss of OC from the soil, and crop growth may add OC into the soil. Given the limitations of the TillTM, caution should be taken when comparing the model estimates to field measurements.

Several assumptions were made in TillTM for the simplification of the model. First, soil bulk density and tillage depth were assumed to be uniform across the landscape and to be constant with time. These are common assumptions in tillage erosion modeling (e.g., Lobb and Kachanoski, 1999a; Schumacher et al., 1999; Van Oost et al., 2000; Li et al., 2007b) due to the fact that accurate measurements of bulk density and tillage depth are usually not available for specific locations across landscapes and time. The effects of the variations in bulk density and tillage depth across the landscape have, in part, been incorporated in the coefficients $A$, $B$, and $C$ in Eq. [5], which were determined by field experiments (Lobb et al., 1999; Li et al., 2007a). Model uncertainty associated with these assumptions could be high, however, for long-term simulation or for topographically complex landscapes. Specifically, when tillage systems change, Eq. [5] needs to be recalibrated and the input tillage depth needs to be reassessed.

An inevitable assumption in TillTM is the maximum translocation distance ($D_{\max}$). Recall that the portion of the translocated soil beyond $D_{\max}$ calculated using Eq. [4] was artificially reassigned to the points within $D_{\max}$. This was associated with another assumption in TillTM: the uniformity of topographic features (i.e., slope gradient and slope curvature) within the translocation distance (Lobb et al., 1995). In other words, the dispersion of the translocated soil from a given location was assumed to be determined only by the topographic features at this given point and not to be affected by the topographic features at subsequent locations. Setting the $D_{\max}$ at 5 m in this study was based on the fact that, in field tillage translocation experiments, soil is very rarely translocated farther than 5 m (e.g., Lindstrom et al., 1999; Lobb et al., 1999; Li et al., 2007a). Nevertheless, a test was conducted to run the model by setting $D_{\max}$ at 10 m. The pattern of the estimated tillage erosion was the same as the original one (i.e., $D_{\max}$ = 5 m) but the estimated tillage erosion rates were found to be greater than the original ones (data not shown). Differences (absolute values) between these two sets of tillage erosion estimates were found to be greatest on the top of the convexities and the bottom of the concavities (up to 15% on the IH, the most topographically complex landscape). Further studies are needed to quantify the uncertainties associated with the TillTM model, especially the errors associated with different settings of $D_{\max}$.

CONCLUSIONS

On topographically simple landscapes, the pattern of tillage erosion does not change greatly with time. On topographically complex landscapes, however, the feedback of the ongoing tillage erosion on topography is substantial. Both soil loss rates at the top of medium-scale convexities and soil accumulation rates at the bottom of medium-scale concavities decrease with time. The effect of tillage pattern (direction) on tillage erosion in the boundary areas is limited across short distances. In the nonboundary areas, the tillage erosion pattern is not considerably influenced by the tillage pattern.

Although there is no soil being moved out of the field, tillage translocation causes the transfer of soil constituents between the till layer and the underlying soil and results in a net loss (e.g., for OC) or gain (e.g., for IC) of soil constituents in the till layer. Landscape topography, tillage pattern, and the length of the tillage period all strongly affect the pattern and intensity of tillage-induced soil constituent redistribution. Assuming tillage is the driving force, soil constituent concentration in the till layer decreases (e.g., for OC) or increases (e.g., for IC) at soil loss positions, i.e., starting boundary areas under one-direction tillage and convexities. This decrease (or increase) builds up and extends to soil accumulation areas with time, especially under one-direction tillage and on topographically complex landscapes. In the sublayer, soil constituent content increases (e.g., for OC) or decreases (e.g., for IC) at soil accumulation positions, i.e., end boundary areas under one-direction tillage and concavities. This increase (or decrease) also builds up with time but does not extend to soil loss areas.

Tested against field measurements, the developed TillTM model demonstrated an adequate estimate of the pattern of soil constituent redistributions with time. Large discrepancies were found between the model estimates and the field measurements, however, due to the limitations and uncertainties associated with the model. The application of TillTM suggests that the dilution of $^{137}$Cs due to tillage translocation could be substantial on topographically complex landscapes and needs to be taken into account in the $^{137}$Cs technique. The fact that tillage translocation causes the vertical redistribution of soil constituents across the landscape implies that tillage translocation is one of the driving forces behind the spatial variability of soil properties and properties that impact biophysical processes such as crop production, nutrient cycling, greenhouse gas emission, and pesticide fate.

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APPENDIX

\[ A \] tillage translocation distance on level land (m) 

\[ AH \] asymmetric hill 

\[ B \] additional tillage translocation due to the effect of slope gradient (m \(^{-1}\)) 

\[ C \] additional tillage translocation due to the effect of slope curvature (m \(^2\) m \(^{-1}\)) 

\[ C_i(x') \] the amount of a soil constituent at location \( x' \) after the tillage operation (kg m \(^{-1}\)) 

\[ C_i(x') \] the amount of a soil constituent at location \( x' \) before the tillage operation (kg m \(^{-1}\)) 

\[ D_{max} \] the maximum translocation distance used in TillTM; the probability of soil being translocated beyond this range was assumed to be zero (m) 

\[ D_t \] tillage depth (m) 

\[ d_x \] mean translocation distance at \( x \) (m) 

\[ I \] data interval (m) 

\[ IC \] soil inorganic carbon 

\[ IH \] irregular hill 

\[ OC \] soil organic carbon 

\[ P_{adj} \] the \( P_{res} \) averaged to each section to the maximum translocation distance (kg m \(^{-1}\)) 

\[ P_{c}(x_0') \] the probability of soil translocated from the section centralized at \( x' \) to the section centralized at \( x'_0 \) (kg kg \(^{-1}\)) 

\[ PD_{x}(x_0') \] the probability density of soil translocated from \( x \) to \( x_0 \) (kg kg \(^{-1}\) m \(^{-1}\)) 

\[ P_{res} \] the residue probability of soil translocated beyond the maximum translocation distance (kg kg \(^{-1}\)) 

\[ PS \] plane slope 

\[ P_{x,TillTM}(x'_0) \] the probability of soil translocated from the section centralized at \( x' \) to the section centralized at \( x'_0 \) used in TillTM (kg m \(^{-1}\)) 

\[ S_{x}(x_0) \] the mass of soil per meter width at \( x_0 \) after a tillage operation (kg m \(^{-1}\)) 

\[ S_{x}(x) \] the mass of soil per meter width at \( x \) before a tillage operation, which is a constant when tillage depth and soil bulk density are considered to be uniform across the landscape (kg m \(^{-1}\)) 

\[ SH \] symmetric hill 

\[ TC \] soil total carbon 

\[ TE(x') \] net soil mass accumulation per meter width at \( x' \) after a tillage operation, a negative value indicating net soil loss (kg m \(^{-1}\)) 

\[ TillTM \] Tillage Translocation Model, a computer program written in VB code 

\[ x_{tr}x \] distance from the original point (m) 

\[ x_{tr}x',x' \] the distance from the original point to the center of the sections (m) 

\[ \theta_{x'} \] slope gradient at \( x' \) (\%) 

\[ \psi_{x'} \] slope curvature at \( x' \) (\% m \(^{-1}\))

REFERENCES


