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Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada

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Abstract

Tillage erosion is a potential contributor to the total soil erosion occurring within cultivated fields. No study has been carried out on tillage erosion associated with cereal-based production systems, which are the predominant form of crop production in the Canadian Prairies. Previous tillage translocation studies have focused on primary tillage implements (i.e. mouldboard and chisel ploughs), with slope gradient normally assumed to be the only factor that affects tillage translocation. Currently, there is a lack of information available with regards to the effect of secondary tillage and seeding implements and of slope curvature toward total tillage translocation and erosion. In this study, 77 plots were established within a field site in southern Manitoba, Canada to examine tillage translocation caused by four tillage implements: air-seeder, spring-tooth-harrow, light-cultivator and deep-tiller. Together, these four implements create a typical conventional tillage sequence for cereal-based production in Canadian Prairies. We determined that secondary tillage implements could be as erosive as primary tillage implements. In addition, the erosivity of the air-seeder was comparable to that of the deep-tiller, the primary tillage implement, when seeding was conducted shortly after the light-cultivator. In the majority of cases, tillage translocation could be explained by slope gradient alone, confirming that slope gradient is the main factor driving tillage translocation. However, slope curvature also significantly affected tillage translocation and should be used for future modeling.

Keywords: Tillage translocation; Tillage erosion; Modeling; Slope curvature; Secondary tillage; Seeding; Cereal-based production

1. Introduction

Tillage erosion is the redistribution of soil within a landscape caused directly by tillage. For a range of landscapes, it has been shown that tillage erosion is a potential contributor to the total soil erosion on cultivated fields (Govers et al., 1999). Lobb et al. (1995) reported that tillage erosion accounted for at least 70% of the total soil loss on hilltops in their studies in Ontario, Canada. Tillage erosion is a direct result of tillage translocation, which is defined as the movement of soil by tillage. Progressive net downslope movement of soil by tillage results in soil loss from convex positions within a landscape and soil accumulation within concave positions.

The magnitude of tillage erosion depends on the erosivity of the tillage operation and the erodibility of the landscape, as described by Lobb and Kachanoski (1999a). Tillage erosivity is determined by the design of the tillage implement (i.e. the type of equipment, the arrangement and geometry of the cutting tools), and how the tillage is operated (i.e. tillage frequency, tillage speed and depth, the match between the tractor

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Nomenclature

A	the intercept of the linear regression equation (m $pass^{-1}$)
AS	air-seeder
ASX	tillage translocation due to air-seeder as affected by the previous tillage operation, one pass of light-cultivator
B	the slope of the linear multiple regression model associated with slope gradient (m $\%^{-1}$ $pass^{-1}$)
c_s	the proportion of tracer quantity calculated from the summation curve at distance x (kg kg^{-1})
c_T	the proportion of untouched tracer on the bottom of the plots, which can be used to estimate tillage depth (kg kg^{-1})
C	the slope of the linear multiple regression model associated with slope curvature (m $\%^{-1}$ m $pass^{-1}$)
D_P	plot depth (m)
D_T	tillage depth (m)
DT	deep-tiller
Extra	the extra effect of combining light-cultivator and air-seeder when compared to the sum of the single passes of these two implements
i	the denotation for the ith tillage operation
L_P	plot length (m)
L_s	a distance exceeding the maximum translocation distance (m)
LC	light-cultivator
LC/AS	light-cultivator followed by air-seeder
LC + AS	the sum of one single pass of light-cultivator and one single pass of air-seeder
n	the number of tillage operations in one full sequence
P_M	model significance level
RR	tracer recovery rate (%)
S_T	tillage speed (m s^{-1})
SH	spring-tooth-harrow
T_L	the average translocation distance over tillage depth over a unit width of tillage (m)
T_M	translocation in mass over a unit width of tillage (kg m^{-1})
T_{Mt}	the total translocation in mass after a full sequence (kg m^{-1})
T_P	the averaged translocation distance over the depth of labeled soil over a unit width of tillage (m)
W_I	implement width (m)
x	the distance at which the quantity of tracer is measured (m)

Greek letters

α	the intercept of the linear regression equation, representing tillage translocation unaffected by slope gradient or slope curvature and indicating the dispersivity of the given tillage operation (kg m^{-1} $pass^{-1}$)
α_p	the intercept of the regression model for the pth percentile (m)
β	the coefficient for slope gradient, representing the extra tillage translocation due to slope gradient and indicating the erosivity of the given tillage operation (kg m^{-1} $\%^{-1}$ $pass^{-1}$)
β_p	the coefficient of slope gradient for the pth percentile ($m\%^{-1}$)
γ	the coefficient for slope curvature, representing the extra tillage translocation due to slope curvature and indicating the erosivity of the given tillage operation (kg m^{-1} ($\%^{-1}$ m) $pass^{-1}$)
γ_p	the coefficient of slope curvature for the pth percentile (m $\%^{-1}$ m)
ε	a measure of error, either from the inherent variability of translocation or experimental error, or from both (%)
θ	slope gradient, positive when downslope and negative when upslope (%)
λ_p	the distance to which p% of soil mass is translocated (m)
ρ	soil dry bulk density (kg m^{-3})
φ	slope curvature, positive for convex and negative for concave (% m^{-1})

and the implement and the behavior of the operator). Any implement that disturbs soil has the potential to cause tillage erosion. Tillage translocation and tillage erosivity must be measured in a much broader range of cropping and tillage systems than what has been examined to date. No one has reported on the erosivity of tillage associated with cereal-based production systems, which are the predominant form of crop production in the Canadian Prairies, the northern-most portion of the North American Great Plains and the largest area of crop production in Canada. Tillage associated with this system a relatively low intensity primary and secondary tillage and relatively high disturbance seeding operations. As well, the size of implements is normally quite large (10–25 m in width), which can result in intensive ‘‘scalping’’ of hilltops.

To date, tillage translocation and tillage erosion studies have been focused on the primary tillage implements, such as mouldboard plough and chisel plough (e.g. Lindstrom et al., 1990, 1992; Lobb et al., 1999). Few studies have been carried out to investigate tillage translocation and tillage erosion caused by secondary tillage and seeding implements; translocation by the former has been assumed to be of minor importance, and translocation by the latter has been assumed to be negligible. These assumptions need to be validated.

Studies of tillage systems have investigated each implement separately (e.g. Lobb et al., 1999) or only investigated combinations (e.g. Lindstrom et al., 1990). But in a sequence of tillage operations, when one operation is conducted shortly after the previous operation, the previous one likely will affect the tillage translocation of the following operations. Lobb et al. (1995) and Lobb and Kachanoski (1999b) investigated tillage translocation caused by the same tillage sequence, combined and separately, respectively, but these two studies were conducted on different soil types. To account for the effect of the previous tillage, Lobb et al. (1999) pre-tilled the field before establishing the plots for the secondary tillage implements, a tandem disc and a field cultivator. Van Muysen et al. (1999, 2000) compared the translocation caused by mouldboard plough and chisel plough on a pre-tilled field to that on a grass fallow field and on a stubble field, respectively. These authors found that pre-tilling considerably increased the intensity of translocation. Marques da Silva et al. (2004), however, found that pre-tilling decreased the translocation caused by an offset disc harrow. It is probable that soil conditions (including crop residue cover) at the time of tillage will affect the translocation of soil, and these conditions will be affected by the preceding soil and crop management tillage and cropping practices. The effect of one operation on subsequent ones must be examined in greater details.

Landscape erodibility is determined by the topographic properties of the landscape (i.e. slope gradient and slope curvature) and properties of the soil (e.g. bulk density, moisture content, texture, structure, etc.). Numerous studies from different parts of the world have shown that slope gradient is the dominant property in influencing tillage translocation and tillage erosion (e.g. Lindstrom et al., 1990; Govers et al., 1994). However, the variability in tillage translocation which causes tillage erosion cannot be explained by slope gradient alone. The effects of other factors such as tillage depth and speed, tillage direction, soil properties have been stressed by several researchers (e.g. Lobb et al., 1999; Van Muysen et al., 2002). Lobb et al. (1999) suggested the inclusion of slope curvature as a second topographic property and used a multiple linear function to simulate tillage translocation

$$T_{\mathrm{M}} = \alpha + \beta\theta + \gamma\varphi \qquad (1)$$

where T_{M} is translocation in mass over a unit width of tillage (kg m^{-1}); α is the intercept of the linear regression equation, representing tillage translocation unaffected by slope gradient or slope curvature (kg m^{-1} pass^{-1}); β is the coefficient for slope gradient, representing the extra tillage translocation due to slope gradient (kg m^{-1} %$^{-1}$ pass^{-1}); θ is slope gradient, positive when downslope and negative when upslope (%); γ is the coefficient for slope curvature, representing the extra tillage translocation due to slope curvature (kg m^{-1} (%$^{-1}$ m) pass^{-1}); and φ is slope curvature, positive for convex and negative for concave (% m^{-1}).

In this model, α, β and γ characterize the tillage erosivity of a given tillage implement or combination of implements, while slope gradient (θ) and slope curvature (φ) characterize the landscape erodibility. These authors found that for some implements, slope curvature has significant effect on tillage translocation, however the effect was not consistent for all the implements. Slope curvature may be of greater importance in the Canadian Prairies where landscapes can be highly topographically complex due to the youth of the landscapes and the short history of cultivation. The effect of slope curvature therefore needs to be examined in depth.

The objectives of this study were: (1) to assess the erosivity of tillage implements and practices associated with cereal-based production systems in Manitoba; (2) to examine tillage translocation by and erosivity of individual tillage implements used in these crop production systems, and, in particular, that of secondary tillage and seeding implements; (3) to examine the effect of one tillage operation on subsequent operations; and (4) to investigate the effect of slope curvature on tillage translocation and its contribution to the erosivity in these production systems.

2. Materials and methods

2.1. Study site

This study was carried out near Deerwood, about 150 km southwest of Winnipeg in Manitoba, Canada, between −98.3° and −98.4° East and 49.3° and 49.4° North. This area is referred to as Pembina Hills Upland (Michalyna et al., 1988), a transition area between the lower Manitoba Plain and the higher Saskatchewan Plain and is characterized by undulating to hummocky moraine landscapes. Climate is a subhumid continental with short, cool summers and long cold winters. In Deerwood, the mean annual temperature is 2.9 °C and the mean annual precipitation is 567 mm. Underlying bedrock of this area is shale but the parent material is dominantly glacial till derived from shale, limestone and granite rock and moderately to very strongly calcareous. The dominant soils in this area are Dark Grey Chernozems (Canadian System of Soil Classification, 1998) (Mollisols in the USDA soil classification system). Soil series vary according to landform positions. On the upper and mid slope positions, soils are well drained and belong to the Dezwood Loam series (Orthic Dark Grey Chernozem); on the lower slope positions, soils are imperfectly drained and belong to the Zaplin Loam series (Gleyed Dark Grey Chernozem); and in the depression positions, soils are poorly drained and belong to the Pouchal Clay Loam series (Humic Luvic Gleysol). For the surface layer, the soil bulk density, based on 72 soil samples collected from the study site after harvest and prior to tillage, was 1170 kg m^{-3} (data not shown). The natural vegetation in this area is boreal forest, but most of the area has been cleared for agriculture and is cultivated. Spring wheat is the most popular crop in this area. Other major crops include canola, barley, dry field beans, oats, alfalfa and flaxseed. In the 2001 census year (Statistics Canada, 2002), these major crops covered about 85% of the seeded area (Fig. 1). The intensity of tillage practices has decreased since 1970s: firstly, conservation tillage and/or zero-till systems have been adopted by more and more farmers; secondly, in conventional tillage systems, lighter implements have been used and used less frequently.

The field site used in this study was broken and has been continuously cropped since 1928. Main crops are spring wheat, oat and canola. Tillage implements used in this field have changed over time. Mouldboard plough for primary tillage, tandem disc and heavy cultivator for secondary tillage, diamond harrow for harrowing and disc drill for seeding were used before 1980s. Currently, the sequence of operations in the field includes one primary tillage operation (deep-tiller), one to two secondary tillage operations (usually a light-cultivator, sometimes a tandem disc, fertilizer usually applied with a secondary tillage), one to two harrowing (spring-tooth-harrow) operations, and seeding (air-seeder) (Fig. 2). The description of the tillage implements currently used is summarized in Table 1. The farmer considers this tillage system to be conventional by today's standard, although the implements being used are considerably less intensive than the traditional definition of conventional tillage.

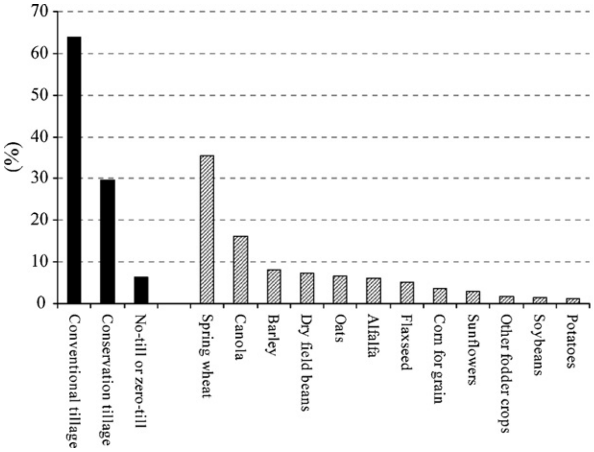

Fig. 1. Tillage systems and main crops in the study area. The height of the bar represents the respective percent of seeded area in 2001 census year in agricultural region 8, Manitoba, Canada. Conventional tillage refers to tillage incorporating most of the crop residue into the soil and conservation tillage refers to tillage retaining most of the crop residue on the surface (*source*: Statistics Canada, 2002).

2.2. Experiment design

In 2003 and 2004, 53 plots were established to measure tillage translocation by single passes of deep-tiller (DT), spring-tooth-harrow (SH), light-cultivator (LC) and air-seeder (AS). Another set of 24 field plots was established to examine the combined effect of light-cultivator and air-seeder (LC/AS) due to the fact that seeding operations is usually conducted very shortly after secondary tillage. In total, there were 77 field plots.

Two areas of the field were selected according to their topographic features (Fig. 3), the long slope area and the bowl area, which represent the two dominant landform types within the field: undulating and hummocky landforms, respectively. The long slope area is part of a large ridge and extends from the top of the ridge to its base, along the northern boundary of the field. Slope gradient in this area ranges from 0% to

Fig. 2. Photos of the four tillage implements: (a) deep-tiller; (b) spring-tooth-harrow; (c) light-cultivator; (d) air-seeder.

about 20% while slope curvature ranges from −2.5 to 2.5% m^{-1}. Although the absolute values of slope gradient are high, the variability along the slope is relatively small because the slope is long (about 500 m). The high extreme slope gradient and slope curvature values in this area provide an excellent opportunity to examine tillage translocation under a wide range of topographic conditions. The bowl area was selected primarily for examining the effect of slope curvature. This area is a complex of small knolls located in the middle of the field. The central part of this area is a depression, which gives it a bowl shape. The ranges of both slope gradient (form 0% to 6%) and slope curvature (from −1.5 to 1.5% m^{-1}) in the bowl area are narrower than that of the long slope area, especially the range of slope gradient. The change in slope curvature is comparatively high given that all the changes happen within a fairly short distance (about 40 m from the edge of the bowl to its base). It was presumed that the relatively small change in slope gradients and large change in slope curvatures in the bowl area would provide for greater isolation of slope curvature's contribution to tillage translocation.

In both the long slope area and the bowl area, plots were oriented into two parallel rows over a range of topographic conditions (i.e. slope gradient and slope curvature), one row undergoing upslope tillage while the other row undergoing downslope tillage. Plot positions for deep-tiller are illustrated in Fig. 3. Plot positions for spring-tooth-harrow and the combination

Table 1
Description of tillage implements

Implement[a]	Type	Tools	Spacing (m [in.])	Arrangement	W_I (m [foot])	D_T (m)	S_T (m s^{-1})
Deep-tiller	Primary	Sweeps 0.25 m (10 in.) wide	0.31 [12]	Four rows	11.0 [36]	0.10–0.13	1.8–2.0
Light-cultivator	Secondary	Sweeps 0.23 m (9 in.) wide	0.18 [7]	Four rows	13.7 [45]	0.04–0.08	2.2–2.5
Spring-tooth-harrow	Harrowing	Spring-tooth 0.53 m (21 in.) long, 0.01 m (0.5 in.) in diameter	0.05 [2]	Five rows	21.3 [70]	0.01–0.02	2.0–2.5
Air-seeder	Seeding	Knives 0.03 m (1 in.) wide	0.18 [7]	Four rows	11.0 [36]	0.02–0.04	2.2

[a] The same tractor, John Deer 8970 (400 horsepower), was used for all the implements.

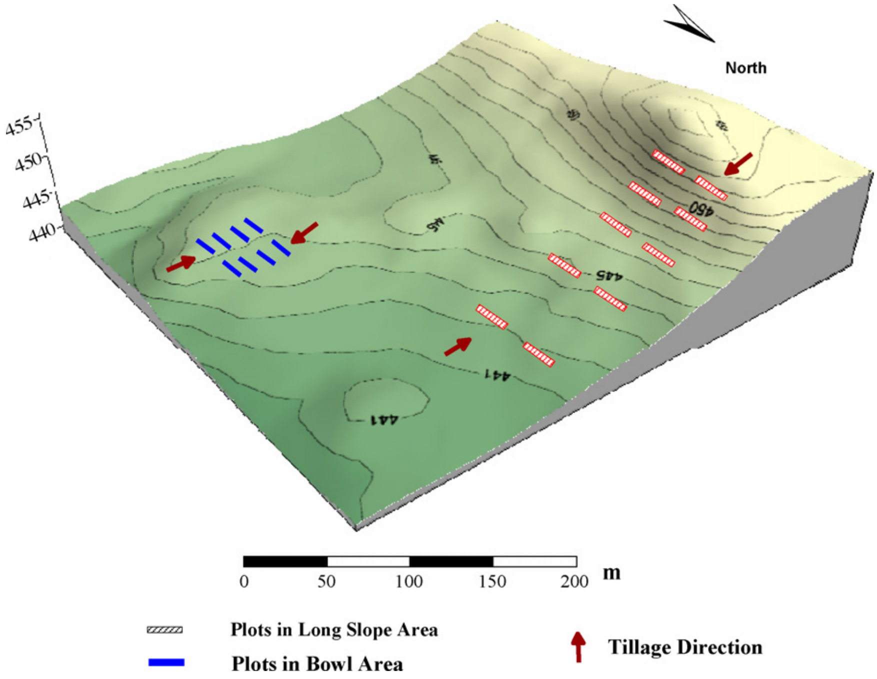

Fig. 3. Plot positions for deep-tiller to illustrate plot layout. Towards the northern boundary is the long slope area, towards the eastern-southern corner is the bowl area. Paired plots were positioned in two parallel lines and tillage operations were undertaken in opposite directions (note: scale used for the plots were different from the map scale. plot width is 1.22 m).

of light-cultivator and air-seeder were similar to those for the deep-tiller. For the single pass of light-cultivator and air-seeder, plots were only established in the long slope area.

2.3. Topographic survey

Plot positions and the topography of the plots areas (area of approximately 10 m × 10 m) were surveyed by using total station (Sokkia set 4110). The survey was georeferenced using a Trimble TSC1 system, a differential GPS system. For the topographic survey, the survey was conducted along two to four lines parallel to the tillage direction at a density of approximately 2–3 m. Slope gradient and slope curvature at the plot position were calculated directly by using these topographic survey points.

2.4. Tillage translocation measurement

Dyed limestone chips were used as tracers to measure soil movement by tillage (MacLeod et al., 2000; Zhang et al., 2004). Tracer size was 0.6–1.2 cm for all tillage operations, excluding deep-tiller. Larger size tracers (1.2–2.5 cm) were used for the deep-tiller to save field labor because the plot size for deep-tiller was considerably larger than that for the other tillage operations (see below for the determination of the plot size) and Rahman et al. (2002) found no significant difference due to tracer size or density.

The tracers were incorporated into the soil in plots. Plots were oriented perpendicular to the tillage direction (Fig. 4). The length of the plots (the dimension along the tillage direction) was 20 cm. The width of the plots (the dimension perpendicular to tillage direction) depended on the arrangement of cutting tools (e.g. sweeps and knives) in the tillage implement. Plot width was equal to a multiple of the tool spacing (Fig. 4a). A compromise was made for the combination of light-cultivator and air-seeder due to the different tool spacings of these two implements. The depth of the plots was 5–10 cm deeper than the expecting tillage depth (Fig. 4b and c). To set up the plot in the field, a base plate and a box (four walls) were prepared in advance. The inside dimensions of the box were made to be the exact size of the plot. Soil in the plot location was dug out first and the plate was placed and leveled on the bottom of the hole. The box was established on the plate and the soil that was excavated was placed back into the hole, both inside and outside the box, and packed to the original bulk density. Soil inside the box was then taken out and mixed with the tracer (a mass equal to about 5% of the soil mass). The labeled soil was placed back into the box once again and the plot was packed to the original bulk

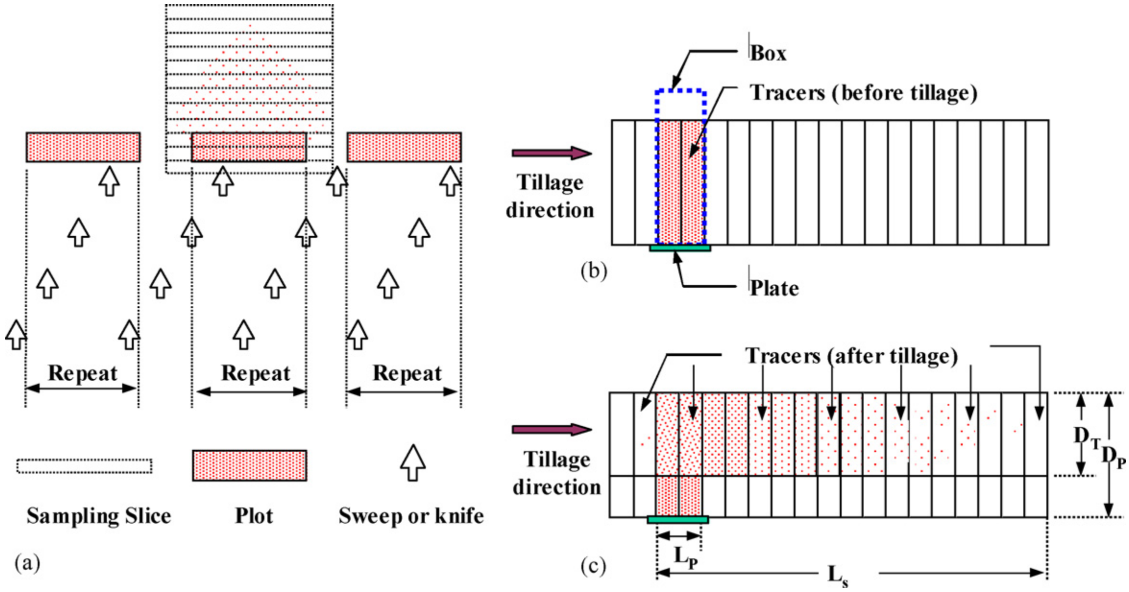

Fig. 4. Illustration of plot set-up and sampling design. (a) Top view. Plot width was determined by the repeating width of the tools according to the tool arrangement of the implement; (b) side view of a plot before tillage. The box is pulled out and the plate is left in the field as a reference for the sampling; (c) side view of a plot after tillage. The plot depth is deeper than the tillage depth, and after tillage only the tracers within the tillage layer are redistributed.

density. Finally, the box was pulled out and the base plate was left in the field as a reference for exact relocation of the plot.

After tillage operations, the edge of the plate was located and used as a reference for sampling. The tracers were recovered along the tillage direction in slices, each 10 cm in length, until no tracers could be found (Fig. 4). The distribution of these plot-tracers was then used to generate a summation curve (Fig. 5) as described by Lobb et al. (2001). Using the summation curve method, what is assessed is the volume/mass moving past the zero line of the tracer-labeled plot. The average translocation distance, and the experimental error, can be calculated through a procedure-involving convolution

$$T_P = \int_0^{\infty} (1 - c_s)\mathrm{d}x - \int_{-\infty}^{0} (c_s)\mathrm{d}x \quad (2)$$

$$\varepsilon = \left(\frac{\int_{L_s}^{L_s+L_p} |1 - c_s|\mathrm{d}x}{T_p + L_p} \right) \times 100 \quad (3)$$

where T_p is the translocation distance averaged over the depth of labeled soil, over a unit width of tillage (m); x is the distance at which the quantity of tracer is measured (m); c_s is the proportion of tracer quantity calculated from the summation curve at distance x (kg kg^{-1}); ε is a measure of error, either from the inherent variability of translocation or experimental error, or from both (%); L_s is a distance exceeding the maximum translocation distance (m); and L_P is plot length (m).

T_p can be converted to translocation in distance, T_L, by

$$T_L = T_P \frac{D_P}{D_T} \quad (4)$$

where T_L is translocation distance averaged over the depth of the tillage layer, over a unit width of tillage (m); D_T is tillage depth (m); and D_P is plot depth (m). T_p can also be converted directly to translocation in mass, T_M, by

$$T_M = \rho T_L D_T = \rho T_p D_P \quad (5)$$

where ρ is dry soil bulk density (kg m^{-3}).

T_L provides an indicator of the potential erosivity since T_L relates to how far soil is moved over the land surface. However, it is preferable to use T_M (translocation in mass) rather than T_L because: (1) traditionally, erosion is measured as a mass; (2) the calculation of T_L requires accurate measurements of tillage depth (Eq. (4)), and it is difficult to determine tillage depth in the field, particularly for tillage implements with sweeps or knives because the cutting surface can be very uneven. The calculation of T_M uses D_P (Eq. (5)), which is accurately measured during the plot set up. Therefore, T_M is considered to be more accurate

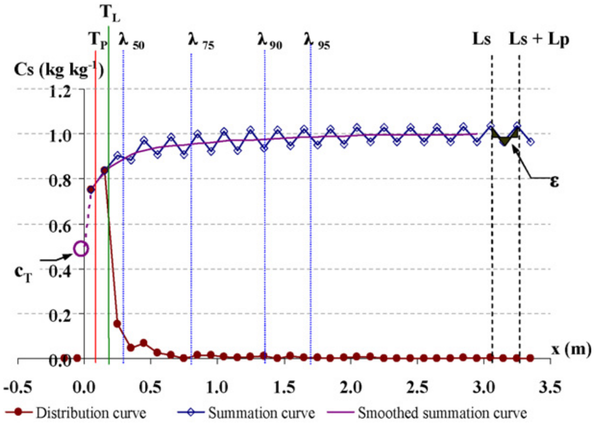

Fig. 5. Tracer distribution and summation curve of deep-tiller, plot 4. Plot depth (D_P) = 0.25 m. c_T represents the proportion of the untouched tracer on the bottom of the plot. Tillage depth (D_T) was estimated by $D_T = D_P(1 - c_T) = 0.13$ m. $T_L = T_P D_P / D_T = 0.23$ m. λ_{50}, λ_{75}, λ_{90} and λ_{95} represent the distances to which 50%, 75%, 90% and 95% of soil mass is translocated, respectively. The inherent variability of tillage translocation and experiment errors associated with the summation curve (ε) was represented by shaded area ($T_P = 0.115$ m, $L_P = 0.20$ m, $L_s = 3.05$ m, ε = 7.6%).

than T_L; (3) since T_L depends on tillage depth, it is not comparable between tillage implements with different tillage depth; (4) tillage depth varies over the landscape. The summation curve method provides an estimate of the tillage depth (Fig. 5). It also provides an approach to estimate the distance to a cumulative percentile of translocated soil mass along tillage direction, e.g. λ_{75} (m) is the distance to which 75% of soil mass (75th percentile) is translocated (Fig. 5). These percentiles characterize the behavior of the translocated soil and how soil is distributed along the path of tillage.

2.5. Statistical analysis

Tillage translocation data were examined with SAS 9.0® for statistical analyses. Means were used to indicate the averages, and standard deviation (S.D.) and coefficient of variance (CV) were used to indicate the variability of the data. A Tukey–Kramer test was used for multiple comparisons and to determine whether there was a significant difference between those means. Due to the inherent variability of the data, 10% significance level was used as the threshold for the Tukey–Kramer tests of multiple comparisons. The Tukey–Kramer test was designed for pairwise comparisons of means with unequal-sized samples. It controls the maximum-experimentwise-error-rate (SAS Institute Inc., 2002).

In the regression analyses, a F-test was used to determine the significance of the regression model and a student t-test was used to determine the significance of the individual coefficients (i.e. α, β and γ). The significance of the tests were indicated by the $P > F$ or $P > |t|$ values, which were grouped into three categories, i.e. ≤ 0.10, ≤ 0.05, ≤ 0.01, and are stated as 10%, 5% and 1% levels, respectively. R^2 was used as another indicator for evaluating to what extent the regression models could explain the observed variation of the dependent variable(s).

2.6. Tillage translocation modelling

Tillage translocation models were established based on the regression analysis of translocation in distance (T_L) or translocation in mass (T_M) against slope gradient (θ) and slope curvature (φ), as shown in Eq. (1). By using Eqs. (1), (4) and (5), the translocation in mass can be calculated by

$$T_M = T_P \rho D_P = T_L \rho D_T = (A + B\theta + c\varphi)\rho D_T = \alpha + \beta\theta + \gamma\varphi \quad (6)$$

where A is the intercept of the linear multiple regression model (m pass^{-1}); B is the slope of the linear multiple regression model associated with slope gradient (m %$^{-1}$ pass^{-1}); and C is the slope of the linear multiple regression model associated with slope curvature (m %$^{-1}$ m pass^{-1}).

β and γ indicate tillage erosivity. The model is more sensitive to β than to γ because the range of slope gradient observed in the field typically exceeds those of slope curvature by about one to two orders of magnitude (Lobb et al., 1999). β is commonly referred to as tillage transport coefficient and has been widely used as the indicator of tillage erosivity. α indicates the dispersivity of translocated soil. In general, the greater is the α value, the wider is the range of the soil being translocated, i.e. the greater the dispersivity is. α also serves as a means for comparison of research data between tillage implements and practices.

In order to examine the contributions of slope gradient (θ) and slope curvature (φ) on tillage translocation, in this study, we used two regression models

$$T_M = \alpha + \beta\theta \quad \text{(M1)}$$

$$T_M = \alpha + \beta\theta + \gamma\varphi \quad \text{(M2)}$$

(M1) is a simple regression model used to examine the effect of slope gradient (θ) as shown in Fig. 6. (M2) is a multiple regression model using both θ and φ as independent variables, which was the model of primary

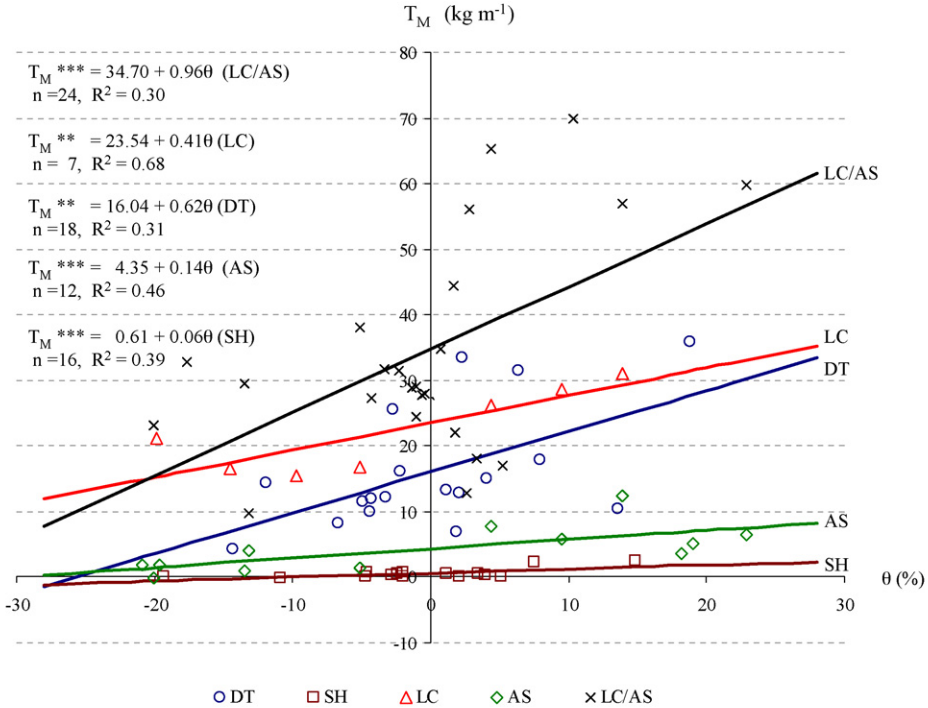

Fig. 6. Regression analyses of translocation in mass (T_M) against slope gradient for each tillage treatment.

interest in this study. (M2) was compared to (M1) to determine whether (M2) could better explain the observed tillage translocation. Data from the long slope area and the bowl area were analyzed separately and then the combined data sets were analyzed as well (Table 3).

Four translocation percentiles, i.e. λ_{50}, λ_{75}, λ_{90} and λ_{95}, were also regressed against slope gradient and/or slope curvature as

$$\lambda = \alpha_p + \beta_p\theta \tag{M3}$$

$$\lambda = \alpha_p + \gamma_p\theta \tag{M4}$$

$$\lambda = \alpha_p + \beta_p\theta + \gamma_p\varphi \tag{M5}$$

where p denotes the pth percentile of translocated soil mass; λ_p is the distance to which p% of soil mass is translocated (m); α_p is the intercept of the regression model for the pth percentile (m); β_p is the coefficient of slope gradient for the pth percentile (m %$^{-1}$); and γ_p is the coefficient of slope curvature for the pth percentile (m %$^{-1}$ m).

These regression models were used to evaluate how slope gradient and slope curvature could affect tillage translocation. More pronounced relationships between soil movement and slope gradient and possibly slope curvature (i.e. greater β_p and γ_p values, respectively) are expected at the higher percentiles (Lobb et al., 2001). However, due to the increased variability that occurs in the tail region of the distribution curves, the significance levels may not be the highest at λ_{95}.

After the translocation models for each tillage operation and their combinations were determined, the overall translocation after a full sequence, which includes several operations, was calculated by

$$T_{\mathrm{Mt}} = \sum_{i=1}^{n} T_{\mathrm{M}i} = \sum_{i=1}^{n}\alpha_i + \left(\sum_{i=1}^{n}\beta_i\right)\theta + \left(\sum_{i=1}^{n}\gamma_i\right)\varphi \tag{7}$$

where T_{Mt} is the total translocation in mass after a full sequence (kg m^{-1}); i is the denotation for the ith tillage operation; and n is the number of tillage operations in one full sequence.

3. Results and discussion

3.1. Tillage translocation

The tillage translocation data are shown in Table 2. Plot positions evenly covered the range of slope gradient (θ) for all the implements and in both areas. Because only one factor could be controlled, slope curvature (φ) is not as evenly distributed as slope gradient, i.e. some plots

Table 2
Summary of tillage translocation data

Plot	Deep tiller (DT)									Spring-tooth-harrow (SH)									Light cultivator followed by air seeder (LC/AS)						
	θ (%)	φ (% m^{-1})	ρ (kg m^{-3})	D_T[a] (m)	RR (%)	T_P (m)	T_L (m)	T_M (kg m^{-1})	ε (%)	θ (%)	φ (% m^{-1})	ρ (kg m^{-3})	D_T[a] (m)	RR (%)	T_P (m)	T_L (m)	T_M (kg m^{-1})	ε (%)	θ (%)	φ (% m^{-1})	ρ (kg m^{-3})	RR (%)	T_P (m)	T_M (kg m^{-1})	ε (%)
Long slope area																									
1	−11.9	2.52	1122	0.09	98.3	0.051	0.146	14.3	18.5	14.8	−0.46	1250	0.02	98.4	0.021	0.139	2.6	9.3	−13.2	1.38	1198	90.8	0.055	9.8	1.9
2	13.6	−0.43	1122	0.10	98.9	0.037	0.094	10.5	0.3	−19.3	−1.03	1250	0.01	98.6	0.002	0.016	0.2	24.4	−20.1	0.08	1214	92.5	0.127	23.0	2.8
3	−14.4	−0.18	1246	0.10	98.7	0.013	0.034	4.2	7.6	7.5	−0.51	1250	0.03	98.2	0.018	0.071	2.2	11.4	−17.7	0.06	1283	92.6	0.170	32.7	3.7
4	18.8	1.09	1246	0.13	97.9	0.115	0.230	35.8	7.6	−10.9	−0.64	1250	0.01	98.4	−0.001	−0.016	−0.1	8.5	−13.4	−0.57	1298	85.1	0.151	29.4	1.3
5	−6.7	−2.19	1246	0.10	98.9	0.026	0.065	8.1	0.1	4.0	0.15	1289	0.01	98.3	0.003	0.059	0.4	8.0	−5.1	0.07	1292	92.1	0.196	38.1	3.0
6	7.9	0.47	1246	0.13	97.9	0.058	0.115	17.9	0.4	−4.7	0.13	1289	0.01	98.0	0.000	0.002	0.0	8.0	−4.3	0.44	1292	90.2	0.141	27.4	7.7
7	−4.4	0.22	1265	0.10	98.4	0.031	0.078	9.9	6.6	2.1	0.41	1201	0.01	98.4	0.001	0.013	0.1	11.7	−2.3	−0.20	1247	87.7	0.169	31.5	0.1
8	2.1	0.05	1265	0.10	98.8	0.041	0.102	12.9	7.6	−2.8	−0.05	1201	0.01	97.9	0.003	0.027	0.3	16.8	−0.4	−0.04	1197	85.0	0.156	28.1	3.8
9	−2.2	−0.15	1166	0.09	97.8	0.055	0.158	16.2	5.6										13.9	1.58	1198	88.8	0.318	57.1	6.2
10	1.9	0.45	1166	0.10	98.4	0.024	0.060	7.0	6.1										22.9	−0.22	1214	92.9	0.328	59.7	5.8
11																			10.4	0.63	1298	88.5	0.359	69.8	2.6
12																			4.4	0.24	1292	87.3	0.337	65.4	6.7
13																			5.2	−0.37	1292	87.8	0.088	17.0	9.9
14																			2.8	1.04	1247	82.1	0.299	56.0	6.1
15																			2.6	−0.48	1197	89.0	0.071	12.8	19.1
Bowl area																									
1	4.1	0.18	1260	0.13	97.6	0.047	0.095	14.9	11.1	3.5	0.47	1260	0.01	97.7	0.004	0.044	0.6	9.2	−3.3	0.63	1260	88.8	0.168	31.7	2.9
2	−4.9	0.11	1208	0.13	97.9	0.038	0.076	11.5	34.8	−2.4	1.11	1208	0.01	98.7	0.004	0.044	0.5	9.5	−1.4	−0.46	1262	91.4	0.153	28.9	4.0
3	6.3	−0.52	1301	0.13	97.1	0.097	0.194	31.6	2.0	5.1	−0.27	1301	0.01	98.8	0.001	0.022	0.1	21.4	0.7	0.00	1216	89.7	0.191	34.8	1.2
4	−4.3	−0.28	1259	0.09	99.0	0.038	0.108	11.9	13.3	−4.6	0.15	1259	0.02	97.5	0.005	0.036	0.7	12.8	−0.7	−0.11	1166	90.9	0.159	27.8	7.7
5	2.3	−1.55	1259	0.13	96.9	0.106	0.212	33.4	5.4	1.1	−0.17	1259	0.01	97.7	0.004	0.036	0.4	8.9	1.7	0.12	1237	93.8	0.119	22.1	6.1
6	−3.2	−1.13	1289	0.09	98.1	0.038	0.107	12.1	2.6	−2.0	−0.27	1289	0.01	99.4	0.001	0.020	0.1	17.2	3.4	0.29	1276	90.3	0.095	18.1	10.8
7	−2.7	1.46	1194	0.14	97.4	0.086	0.156	25.5	8.0	−1.9	0.11	1194	0.02	99.6	0.007	0.048	0.9	16.0	1.7	−0.10	1324	89.7	0.224	44.4	4.5
8	1.1	0.14	1301	0.09	99.1	0.041	0.116	13.2	10.9	2.1	0.10	1301	0.01	98.8	0.001	0.020	0.1	15.6	−1.0	−0.21	1305	92.9	0.149	29.1	9.1
9																			−1.0	0.45	1237	91.5	0.131	24.4	13.5
Average[b]	1231	0.11	98.2[c]				16.2	8.2[a,b]				1253	0.01	98.4[c]			0.6	13.0[b,c]			1252	89.6[b]		3.41	5.8[a]
S.D.	56	002	0.7				9.3	8.2				36	0.01	0.6			0.8	5.0			44	2.8		16.4	4.3

Plot	Light cultivator (LC)									Air seeder (AS)								
	θ (%)	φ (% m^{-1})	ρ (kg m^{-3})	D_T[a] (m)	RR (%)	T_P (m)	T_L	T_M	ε (%)	θ (%)	φ (% m^{-1})	ρ kg m^{-3})	D_T[a] (m)	RR (%)	T_P (m)	T_L	T_M	ε (%)
Light slope area																		
1	−9.7	1.26	1198	0.07	86.8	0.087	0.193	15.6	0.9	−13.2	1.38	1198	0.03	95.1	0.034	0.115	4.1	6.9
2	−19.9	0.06	1283	0.09	85.1	0.110	0.183	21.2	8.2	−20.1	0.33	1214	0.02	97.6	−0.001	−0.007	−0.1	37.4
3	−14.5	−0.44	1298	0.06	81.7	0.085	0.212	16.5	12.0	−20.9	−0.46	1283	0.04	97.6	0.015	0.044	2.0	9.7
4	−5.1	−0.33	1292	0.08	88.4	0.086	0.172	16.7	7.2	−13.4	−0.57	1298	0.02	96.8	0.008	0.054	1.1	3.4
5	13.9	1.58	1198	0.09	69.1	0.172	0.287	31.0	7.3	13.9	1.58	1292	0.04	93.4	0.096	0.240	12.4	14.9
6	9.5	−0.52	1298	0.08	79.5	0.148	0.268	28.7	3.6	22.9	−0.22	1198	0.04	97.4	0.054	0.135	6.4	5.5
7	4.4	−0.06	1292	0.09	88.0	0.136	0.226	26.3	6.9	19.1	−0.26	1214	0.06	97.0	0.042	0.077	5.1	19.6
8										−5.1	−0.3	1283	0.02	94.9	0.011	0.075	1.4	17.0
9										9.5	−0.5	1298	0.04	94.7	0.046	0.130	5.9	2.0
10										4.4	−0.1	1292	0.04	99.7	0.060	0.171	7.7	8.4
11										18.2	−2.5	1283	0.04	99.0	0.029	0.080	3.7	21.4
12										−19.7	0.6	1283	0.04	98.3	0.014	0.041	1.8	27.6
Average[b]			1266	0.08	82.7[a]			22.3	6.6[a,b]			1261	0.03	96.8[c]			4.3	14.5[c]
S.D.			46	0.01	6.8			6.4	3.5			42	0.01	1.9			3.5	10.7

[a] Estimated using the summation curve method. Plot depth for DT, SH, LC, LC/AS were 0.25, 0.10, 0.15 and 0.15 m, respectively. For AS, plot depth of plot 11 and 12 were 0.18 and 0.175 m, respectively, and of all the other plots were 0.10 m.
[b] Different letters denote different groups according to Tukey–Kramer test of multiple comparisons at 10% significance level.

have very similar φ values. However, the range of slope curvature (φ), i.e. typical and extreme φ values have also been covered. The estimated average tillage depth for DT, SH, LC and AS was 0.11, 0.01, 0.08 and 0.03 m (Table 2), respectively. These estimates corresponded well with our field measurements (3–10 measurements for each implement, data not shown). T_L calculated based on the estimated tillage depth was highly variable within the same implements (Table 2). T_M was also highly variable within implements. Firstly, the CVs of T_M were high, 57%, 133%, 29%, 82% and 48% for DT, SH, LC, AS and LC/AS, respectively. Secondly, plots with similar topographic features (i.e. similar θ and φ values) have considerably different T_M values (e.g. DT long slope area plot 8 versus plot 10). However, the differences between the implements were obvious. The order of the averages (least square means) of T_M for implements was SH < AS < DT < LC < LC/AS. The T_M for LC/AS, LC and DT were in the same order of magnitude and exceeded the T_M for AS by about one order of magnitude, which in turn exceeded the T_M for SH by about another one order of magnitude. So, in respect to tillage translocation, LC/AS, LC and DT were much more intensive than AS, and AS was much more intensive than SH. It is important to note that AS and SH do move soil and need to be taken into account for tillage erosion studies.

3.2. Deep-tiller

The results of the regression analyses are summarized in Table 3. For deep-tiller, in the long slope area (M1) was significant at 5% level, which indicates that tillage translocation is significantly affected by slope gradient. The R^2 of (M2) (0.59) was greater than that of (M1) (0.45). This improvement of (M2) was attributed to the contribution of slope curvature because the only change from (M1) to (M2) is that slope curvature has been added into the model. Therefore for DT, slope curvature has an effect on tillage translocation.

Data from the bowl area are much more difficult to explain. Neither model was significant. A stronger relationship between tillage translocation and slope curvature was not found, contrary to what was expected. This could be explained by the narrower range of both slope gradient and slope curvature in this area. Generally, the narrower the independent data range is, the more difficult it is to establish a significant regression line. For the both areas (M1) was significant at the 5% level. γ in (M2) was not significant, but (M2) was significant at the 10% level and R^2 of (M2) (0.32) was almost the same as that of (M1).

For the regression of the translocation percentiles (Table 4), the general pattern is that the values of α_p, β_p and γ_p all increase as the percentile increases. In addition, the amount of per percentile increase of the α_p values increases with the respective increase of percentiles. Taking the both areas data as an example (Fig. 7) $(\alpha_{95} - \alpha_{90})/(95 - 90) > (\alpha_{90} - \alpha_{75})/(90 - 75) > (\alpha_{75} - \alpha_{50})/(75 - 50) > \alpha_{50}/50$, indicating that most soil was translocated within a short distance and in the tail region, the soil was distributed in a much wider range, e.g. 75% within about 0.56 m but 20% for the next about 0.58 m (from about 0.56 to 1.14 m). This pattern is also illustrated on the summation curve (Fig. 5). The respective increases of β_p and γ_p values with the increase of percentiles indicate the stronger effect of slope gradient and slope curvature in the tail region. For (M3), β_{50} was extremely low (0.002 m $\%^{-1}$), indicating that slope gradient has almost no effect within the corresponding distance (about 0.29 m). β_{95} was much greater (0.019 m $\%^{-1}$) and (M3) was significant at the 10% level, indicating that within the range of the two percentiles (from about 0.29 to 1.14 m), the amount of soil being translocated is strongly affected by slope gradient. Similarly, for (M4), γ_p value increases considerably with the increase of the percentiles indicating the more profound effect of slope curvature in the tail region. For (M5), β_p and γ_p values were very close to those of (M3) and (M4) of the respective percentiles, respectively, but the R^2 values were much greater than either those of (M3) or (M4) of the respective percentiles, indicating the possible interaction between slope gradient and slope curvature and that including both slope gradient and slope curvature might explain the translocation better.

3.3. Spring-tooth-harrow

For spring-tooth-harrow, in long slope area (M1) was significant at the 5% level (Table 3). Compared to (M1), (M2) had a slightly higher significance ($\ll$0.01 versus 0.03) and both β and γ in (M2) were significant at 1% level. Furthermore, the R^2 of (M2) (0.95) was much greater than that of (M1) (0.56). The comparison of (M2) to (M1) strongly supports that, in the case of SH, slope curvature has significant effect on tillage translocation and (M2) was significantly superior to (M1).

The results of the bowl area data for SH were similar to that of DT. Neither model was significant. For the

Table 3
Summary of regression analyses of T_M against slope gradient and slope curvature

Regression model	Model			Intercept	Slope gradient		Slope Curvature	
	n	$Pr > F$	R^2	$\alpha^{\dagger}$	β	$Pr > \|t\|$	γ	$Pr > \|t\|$
Deep-tiller (DT)								
Long slope area								
$T_M = \alpha + \beta\theta$	10	0.03	0.45	13.41	0.56	0.03	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	10	0.04	0.59	12.90	0.54	0.03	2.82	0.16
Bowl area								
$T_M = \alpha + \beta\theta$	8	0.13	0.35	19.47	1.31	0.13	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	8	0.34	0.35	19.33	1.28	0.18	−0.69	0.86
Both areas								
$T_M = \alpha + \beta\theta$	18	0.02	0.31	16.04	0.62	0.02	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi^{a,b}$	18	0.06	0.32	16.02	0.62	0.02	0.90	0.63
Spring-tooth-harrow (SH)								
Long slope area								
$T_M = \alpha + \beta\theta$	8	0.03	0.56	0.80	0.07	0.03	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	8	≪0.01	0.95	0.46	0.10	≪0.01	−1.50	≪0.01
Bowl area								
$T_M = \alpha + \beta\theta$	8	0.21	0.25	0.44	−0.04	0.21	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	8	0.36	0.34	0.41	−0.03	0.32	0.18	0.45
Both areas								
$T_M = \alpha + \beta\theta$	16	0.01	0.39	0.61	0.06	0.01	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi^{a,b}$	16	0.01	0.51	0.59	0.07	≪0.01	−0.54	0.10
Light cultivator (LC)								
Long slope area								
$T_M = \alpha + \beta\theta$	7	0.02	0.68	23.54	0.41	0.02	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi^{a}$	7	0.10	0.68	23.59	0.42	0.05	0.19	0.72
Air-seeder (AS)								
Long slope area								
$T_M = \alpha + \beta\theta$	12	0.01	0.46	4.35	0.14	0.01	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi^{a}$	12	≪0.01	0.77	4.52	0.18	≪0.01	1.95	0.01
Light-cultivator followed by air-seeder (LC/AS)								
Long slope area								
$T_M = \alpha + \beta\theta$	15	0.01	0.38	38.16	1.01	0.01	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	15	0.03	0.44	36.42	0.97	0.02	7.03	0.30
Bowl area								
$T_M = \alpha + \beta\theta$	9	0.64	0.03	29.05	−0.68	0.64	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi$	9	0.67	0.12	29.51	−0.81	0.60	−6.79	0.46
Both areas								
$T_M = \alpha + \beta\theta$	24	0.01	0.30	34.70	0.96	0.01	–	–
$T_M = \alpha + \beta\theta + \gamma\varphi^{a,b}$	24	0.01	0.35	33.53	0.93	0.01	6.53	0.20

[a] The model used for the respective implement.
[b] Coefficients being used to generate the translocation model for a full sequence.
[†] All significant at 1 % level.

both areas (M2) was significant at the 1% level, γ in (M2) is significant at 10% level, and the R^2 of (M2) (0.51) was greater than that of (M1) (0.39), which confirms the conclusion drawn from the long slope area: (M2) was superior to (M1) and including slope curvature as a secondary factor has improved the model with respect to explaining the observed tillage translocation. The patterns of α_p, β_p and γ_p in (M3)–(M5) for SH, especially in the long slope area, were similar to those for DT (Table 4).

Table 4
Summary of regression analysis of translocation percentiles ($T_{L\ p}$)over slope gradient and/or slope curvature

	n	$\lambda_p = \alpha_p + \beta_p\theta$ (M3)				$\lambda_p = \alpha_p + \gamma_p\varphi$ (M4)				$\lambda_p = \alpha_p + \beta_p\theta + \gamma_p\varphi$ (M5)				
		α_p[a]	β_p[b]	R^2	P_M	α_p[a]	γ_p[b]	R^2	P_M	α_p[a]	β_p	γ_p	R^2	P_M
Deep-tiller (DT)														
Long slope area														
λ_{50}	10	0.28	0.001	0.03		0.27	0.041	0.37	*	0.27	0.001	0.041*	0.40	
λ_{75}	10	0.54	0.006	0.12		0.53	0.098	0.40	*	0.53	0.006	0.096*	0.50	*
λ_{90}	10	0.94	0.012	0.13		0.90	0.201	0.42	**	0.90	0.011	0.197**	0.52	*
λ_{95}	10	1.17	0.020	0.21		1.14	0.211	0.29		1.14	0.019	0.204	0.47	
Bowl area														
λ_{50}	8	0.30	0.011	0.36		0.30	−0.005	0.00		0.30	0.011	0.006	0.36	
λ_{75}	8	0.58	0.015	0.16		0.58	0.034	0.04		0.59	0.017	0.051	0.25	
λ_{90}	8	0.90	0.016	0.09		0.91	0.063	0.06		0.92	0.020	0.083	0.20	
λ_{95}	8	1.10	0.012	0.03		1.12	0.084	0.07		1.13	0.017	0.101	0.12	
Both area														
λ_{50}	18	0.29	0.002	0.06		0.29	0.024	0.11		0.29	0.002	0.024	0.17	
λ_{75}	18	0.56	0.007	0.11		0.56	0.073	0.21	*	0.56	0.007	0.073**	0.32	*
λ_{90}	18	0.92	0.013	0.12		0.92	0.156	0.29	**	0.92	0.013	0.156**	0.41	**
λ_{95}	18	1.14	0.019	0.16	*	1.14	0.172	0.22	**	1.14	0.019*	0.172**	0.38	**
Spring-tooth-harrow (SH)														
Long slope area														
λ_{50}	7	0.19	0.000	0.00		0.16	−0.125	0.63	**	0.16	0.002	−0.140**	0.71	*
λ_{75}	7	0.32	0.004	0.13		0.29	−0.142	0.34		0.28	0.007	−0.191*	0.68	
λ_{90}	7	0.48	0.007	0.17		0.44	−0.218	0.34		0.42	0.012*	−0.301**	0.75	*
λ_{95}	7	0.57	0.011	0.27		0.52	−0.243	0.27		0.50	0.017**	−0.362**	0.80	**
Bowl area														
λ_{50}	8	0.20	−0.003	0.08		0.20	0.011	0.03		0.20	−0.002	0.007	0.09	
λ_{75}	8	0.35	−0.005	0.10		0.35	0.021	0.03		0.35	−0.005	0.011	0.10	
λ_{90}	8	0.53	−0.011	0.13		0.53	0.016	0.01		0.53	−0.011	−0.005	0.13	
λ_{95}	8	0.64	−0.017	0.22		0.63	0.029	0.01		0.64	−0.018	−0.004	0.22	
Both area														
λ_{50}	15	0.20	0.000	0.00		0.19	−0.011	0.15		0.19	0.000	−0.044	0.15	
λ_{75}	15	0.34	0.003	0.06		0.34	−0.040	0.05		0.34	0.004	−0.048	0.13	
λ_{90}	15	0.51	0.005	0.08		0.51	−0.068	0.06		0.50	0.006	−0.081	0.16	
λ_{95}	15	0.60	0.008	0.12		0.60	−0.068	0.03		0.60	0.009	−0.088	0.18	
Light-cultivator (AS)														
Long slope area														
λ_{50}	7	0.30	0.003	0.47	*	0.29	0.006	0.01		0.31	0.003	−0.005	0.47	
λ_{75}	7	0.59	0.005	0.31		0.58	−0.008	0.00		0.60	0.005	−0.028	0.35	
λ_{90}	7	0.94	0.006	0.22		0.93	−0.032	0.03		0.96	0.006	−0.056	0.31	
λ_{95}	7	1.16	0.006	0.18		1.16	−0.053	0.08		1.18	0.007	−0.079	0.34	
Air-seeder (AS)														
Long slope area														
λ_{50}	11	0.23	0.001	0.09		0.24	0.016	0.05		0.24	0.002	0.023	0.18	
λ_{75}	11	0.44	0.004	0.15		0.44	0.026	0.03		0.44	0.004	0.045	0.24	
λ_{90}	11	0.69	0.006	0.19		0.70	0.043	0.04		0.69	0.007	0.072	0.30	
λ_{95}	11	0.86	0.008	0.29	*	0.87	0.047	0.04		0.86	0.010*	0.087	0.42	
Light cultivator followed by air-seeder (LC/AS														
Long slope area														
λ_{50}	15	0.37	0.006	0.60	***	0.35	0.032	0.06		0.36	0.006***	0.020	0.62	***
λ_{75}	15	0.68	0.010	0.62	***	0.66	0.045	0.04		0.68	0.010***	0.025	0.63	***
λ_{90}	15	1.05	0.013	0.64	***	1.03	0.051	0.03		1.05	0.013***	0.024	0.64	***
λ_{95}	15	1.29	0.014	0.62	***	1.27	0.050	0.02		1.29	0.014***	0.020	0.63	***

Table 4 (*Continued*)

	n	$\lambda_p = \alpha_p + \beta_p\theta$ (M3)				$\lambda_p = \alpha_p + \gamma_p\varphi$ (M4)				$\lambda_p = \alpha_p + \beta_p\theta + \gamma_p\varphi$ (M5)				
		α_p[a]	β_p[b]	R^2	P_M	α_p[a]	γ_p[b]	R^2	P_M	α_p[a]	β_p	γ_p	R^2	P_M
Bowl area														
λ_{50}	9	0.44	0.032	0.24		0.43	0.209	0.27		0.43	0.037*	0.233*	0.57	*
λ_{75}	9	0.74	0.041	0.68	***	0.107	0.13			0.73	0.043***	0.136**	0.89	***
λ_{90}	9	1.07	0.017	0.11		1.07	0.021	0.00		1.07	0.018	0.033	0.12	
λ_{95}	9	1.28	−0.004	0.00		1.29	−0.073	0.02		1.29	−0.005	−0.076	0.02	
Both area														
λ_{50}	24	0.40	0.007	0.29	***	0.39	0.043	0.04		0.39***	0.006	0.033	0.31	**
λ_{75}	24	0.70	0.011	0.54	***	0.69	0.044	0.03		0.70	0.010***	0.027	0.55	***
λ_{90}	24	1.06	0.013	0.56	***	1.04	0.042	0.02		1.06	0.013***	0.022	0.56	***
λ_{95}	24	1.29	0.014	0.43	***	1.27	0.032	0.01		1.29	0.014***	0.010	0.43	***

* Model or coefficient significant at 10% level.
** Model or coefficient significant at 5% level.
*** Model or coefficient significant at 1% level.
[a] All significant at 1% level.
[b] Significance level the same as that of the model.

3.4. Light-cultivator and air-seeder

Due to time limitations, plots for light-cultivator and air-seeder were only established in the long slope area. For light-cultivator (M2) was significant but compared to (M1), (M2) had a lower significance (0.10 versus 0.02); the R^2 of (M2) (0.68) was the same as the R^2 of (M1) (0.68, which is the highest R^2 value for (M1) found among all the examined implements) and γ in (M2) was not significant (Table 3). All of these indicate that, for LC, slope gradient has largely explained the observed translocation.

For air-seeder, the significances of (M2) and (M1) were similar ($\ll$0.01vs 0.01), but the R^2 of (M2) (0.77) was much greater than that of (M1) (0.46) and γ in (M2) was significant at 1% level. All of these indicate that (M2) is superior to (M1) in explaining the observed translocation data. Therefore, slope curvature was considered to have a significant effect on tillage translocation for the AS. The patterns of α_p, β_p and γ_p in (M3)–(M5) for AS were similar to those for DT, which also indicate the possible strong effect of slope gradient and slope curvature, especially in the tail region (Table 4).

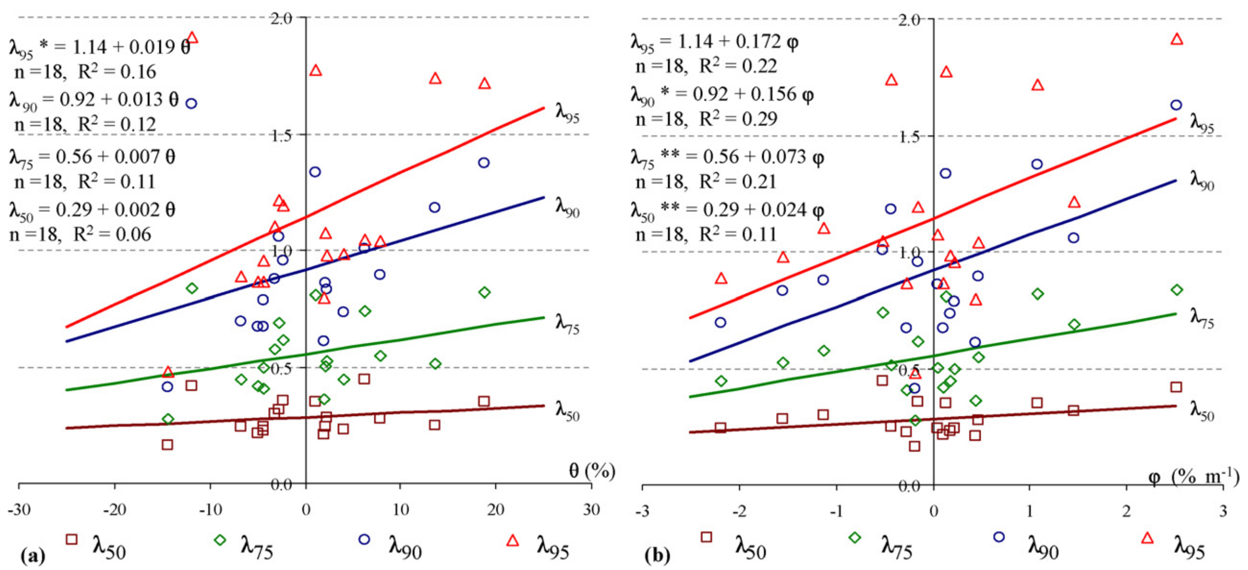

Fig. 7. Regression analysis for deep-tiller (D_T), both areas data of translocation percentiles (λ_{50}, λ_{75}, λ_{90} and λ_{95}) against: (a) slope gradient; (b) slope curvature.

3.5. Light-cultivator followed by air-seeder

For LC/AS, in the long slope area, the significance of (M2) (0.03) and the R^2 of (M2) (0.44) were similar to those of (M1) (0.01 and 0.38, respectively) (Table 3). γ in (M2) was not significant. For the both areas, compared to (M1), (M2) also had similar R^2 value (0.35 versus 0.30) and significance level (0.01 versus 0.01). The significance of γ in (M2) (0.20) exceeded the 10% level. The translocation percentiles analyses also show the strong effect of slope gradient (much higher R^2 values and significance levels of (M3) when compared to those for other implements, of the respective percentile) (Table 4). The effect of slope curvature might be masked by the effect of slope gradient, given that slope curvature was considered as a secondary factor in the models.

3.6. Comparison of the implements

Based on the statistic analyses (M2) established on the both areas data (for DT, SH and LC/AS) and on the long slope area data (for LC and AS) was chosen as the tillage translocation model for the respective implements (Tables 3 and 5).

Of the four implements, LC has the highest α value while DT has the highest β and γ values. The α value for LC (23.59 kg m^{-1}) was about one and a half of that for DT (16.02 kg m^{-1}), demonstrating that LC moves considerably more soil than DT, i.e. dispersivity of LC is higher. This is probably due to the fact that tillage speed of LC is higher than DT and the overlaps between cutting tools in LC (Table 1). The β and γ values for LC (0.42 kg $\%^{-1}$ m^{-1} and 0.19 kg $\%^{-1}$ m m^{-1}, respectively) were considerably lower than those of DT (0.62 kg $\%^{-1}$ m^{-1} and 0.90 kg $\%^{-1}$ m m^{-1}, respectively). Taking both β and γ into account, it is reasonable to conclude that, with respect to erosivity, LC was considerably lower than DT. For AS, the α value (4.52 kg m^{-1}) was only about one third of that for DT and about one fifth of that for LC, and the β value (0.18 kg $\%^{-1}$ m^{-1}) was about one third of that for DT and one half of that for LC, indicating that both the dispersivity and erosivity of AS was much lower than those of LC and DT. For SH, the α value (0.59 kg m^{-1}) was about one order of magnitude lower than that for AS and both the β and γ values (0.07 kg $\%^{-1}$ m^{-1} and -0.54 kg $\%^{-1}$ m m^{-1}, respectively) were much lower than those for AS, indicating that the dispersivity and erosivity of SH were considerably lower than AS. Compared to those for DT and LC, both the dispersivity and erosivity of AS and SH were considerably lower, which was not a surprise. What is important is that the effects of AS and SH were not negligible. Based on a simple calculation on the β value ($4\ \beta_{AS} > 9\ \beta_{SH} > \beta_{DT}$), tillage erosion after four passes of AS or nine passes of SH will exceed one pass of DT.

For the combination of light-cultivator and air-seeder (LC/AS), both α and β values exceed the summation of those for the two single passes (LC + AS) by about 30%. Since for LC, the conditions for the single pass and the combination were the same, the extra translocation was presumed to be caused by the effect of LC on AS. The magnitude of this effect (referred to as Extra) was estimated by subtracting the translocation of both LC and AS from the translocation of the combination: Extra = LC/AS − LC − AS, which gave us the model for the Extra (Table 5). Compared to AS, the Extra exceeded AS itself on both dispersivity and erosivity given that the values of α, β and γ of Extra were all greater than those of AS, respectively. To think of it another way, the translocation due to AS as affected by LC (referred to as ASX) can be estimated by subtracting the translocation of LC from the translocation of the combination: ASX = LC/AS − LC, which gave us the model for ASX (Table 5). Compared to the models of the other implements, dispersivity and erosivity of ASX were found close to those of DT. The effect of air-seeder, based on this point of view, was far from negligible and should be taken into account. The extra effects also suggested that pre-tilling must be taken into account when measuring translocation due to a tillage operation, which is conducted shortly after previous tillage operation(s) and taking the measurement separately without considering the previous tillage operation(s) might considerably under estimate the overall translocation. Our explanations for these extra effects were: (1) More power acts on moving the soil because less power is required for cutting and lifting the soil; (2) With less cohesion and adhesion, soil particles are more likely to move (e.g. rolling) under the effect of gravity; (3) the furrow pattern generated by LC may match up with the AS cutting tools to increase the translocation by AS.

3.7. The effect of slope curvature

Except for the bowl area datasets (M1) was found significant for all the implements, indicating the strong effect of slope gradient on tillage translocation. In contrast, similar simple regression of T_M against slope curvature (data not shown) was found not to be significant for all the implements. However, with the inclusion of slope curvature (M2) explains the observed

Table 5
Summary of results from this study and those of other researchers

Data source	Implement	ρ (kg m^{-3})	S_T (m s^{-1})	D_T (m)	α (kg m^{-1})	β (kg m^{-1} %$^{-1}$)	γ (kg %$^{-1}$)	P_M	R^2	n
This study (Manitoba, Canada)	Deep tiller	1230	1.90	0.11	16.02	0.62	0.90	*	0.32	18
	Spring-tooth-harrow	1250	2.35	0.01	0.59	0.07	−0.54	***	0.51	16
	Light cultivator	1250	2.23	0.08	23.59	0.42	0.19	*	0.68	7
	Air seeder	1270	2.23	0.03	4.52	0.18	1.95	***	0.77	12
	Light cultivator and air seeder	1260			33.53	0.93	6.53	***	0.35	24
	One full sequence				50.73	1.69	6.35			
	Extra[a]				5.42	0.33	4.39			
	ASX[a]				9.94	0.51	6.34			
Van Muysen and Govers (2002) (Huldenberg, Belgium)	Rotary harrow and seeder	1130	2.20	0.07	29.9	1.23		**	0.51	10
Van Muysen et al. (2000) (Huldenberg, Belgium)	Chisel plough[b]	1560	1.57	0.15	53.8	1.69[c]		***	0.51	56
	Chisel plough[d]	1250	2.02	0.20	102.5	3.38[c]		***	0.67	24
Lobb et al. (1999)[e] (Ontario, Canada)	Chisel plough	1580	2.66	0.17	54.8	1.03	3.34	**	0.27	19
	Field cultivator	1210	1.92	0.15	56.7	0.07	−3.63	*	0.11	23
Lobb (1998)[e] (Ontario, Canada)	One conventional tillage sequence[f]	1520	0.8–1.1	0.10–0.19	81.6	5.41	38.89	***	0.66	16
Poesen et al. (1997) (Murcia, Spain)	Duckfoot chisel	1580	0.65	0.16	n.a.	2.82		n.a.	0.78	5
	Duckfoot chisel[j]	1580	0.65	0.14	n.a.	1.39		n.a.	0.65	5
Govers et al. (1994)[e] (Huldenberg, Belgium)	Chisel plough	1350	1.25	0.15	73	1.11		*	0.39	12

n.a.: data not available.
[a] Refer to the text for the explanation of the term.
[b] Stubble soil surface.
[c] Assuming upslope translocation to be constant.
[d] Pre-tilled soil surface.
[e] After Lobb et al., 1999.
[f] One pass of mould plough, two passes of tandem disc, one pass of field cultivator.
[j] Lateral translocation.
* Model or coefficient significant at 10% level.
** Model or coefficient significant at 5% level.
*** Model or coefficient significant at 1% level.

tillage translocation better than (M1) in most cases (except for LC), indicating the necessity of taking slope curvature as a secondary factor into tillage translocation modeling. The insignificance of the effect of slope curvature probably is due to the fact that very few data points ($n = 7$) were available and, therefore, requires further investigation to adequate statistical evidence.

The negative γ value found for SH means tillage translocation on the concave positions exceeds that on the convex positions, which contradicts the theoretical relationship (Lobb and Kachanoski, 1999a). However this might be a special feature of SH under the examined scale given that the R^2 of (M2) was so high (0.95) when compared to that of (M1) (0.56) (Table 3). A possible reason for that is the lead effect, defined by Lobb et al. (1999) as the translocation affected by the position of the tractor. These authors suggested that the magnitude of lead effect to be determined by ''the distance between the center of the tillage implement and the center of the combined mass of the tractor, implement and the soil being carried by the tillage tools''. This is due to the fact that the topography at the position of the tractor wheels determines tillage speed and tillage depth and, therefore, affects the intensity of tillage translocation. The size of the SH is large, which means that the center of the tillage implement was further behind the wheels when compared to other implements. On the other hand, SH caries very little soil during the operation so that the combined mass approaches the tractor. Both of these enhance the lead effect.

The analysis of the translocation percentiles suggests that the effect of slope gradient and/or slope curvature is more profound in the tail region of the distribution curve but due to the inherent variability of tillage translocation, noise increases in the tail region as well, which might mask the effect of slope gradient and/or slope curvature. This masking effect is comparatively stronger for slope curvature because the effect of slope curvature is considerably less significant than slope gradient. Therefore, more data are required for testing the effect of slope curvature and obtaining an accurate γ value than those for testing the effect of slope gradient and obtaining an accurate β value.

Another approach to test the effect of slope curvature is to isolate the effect slope curvature from the effect of slope gradient, as we tried on the bowl area. However, the bowl area data show no physical evidence of the stronger effect of slope curvature when compared to the long slope area data. Part of the problem with the bowl area is the possible stronger lead effect in this area. In this study, the scale of tillage and the scale of the topographic features in the bowl area are such that the effects of slope gradient and curvature on soil movement are confounded by the fact that the implements are quite large relative to the size of the land surface feature. Consequently, what is observed as soil movement at one point can be greatly affected by what is occurring all across the frame of the implement and at some distance in front of the implement, as topography affects the operation of the tractor, the lead effect. Lobb et al. (1999) suggested using the topographic data of the points in front of the plots positions (closer to the tractor) for the regression analysis. Further study on the effect of slope curvature might need a different experiment design to isolate slope curvature from slope gradient.

3.8. Comparison of this study to those of other researchers

Some of the published tillage translocation data is summarized in Table 5. For the same type of implements, large differences exist between different studies. This is understandable since implements may have very different designs, and the operations in different part of the world can be very different. Furthermore, the materials and methods used to measure tillage translocation vary among researchers and, therefore, systematic errors between results may exist. However, these errors are expected to be less than the experimental errors. A weakness in all of the studies is the small dataset.

The large differences between different researchers make comparisons difficult. For the single implements, both α and β values of deep-tiller found in this study were considerably lower than those found by other researchers of chisel plough, indicating that the dispersivity and erosivity of the primary implement used in this study was considerably lower. Other than the different design of the implements, lower soil bulk density and shallower tillage depth observed in this study might be the major reasons for the less intensive dispersivity and erosivity. α and β values for the combination of light-cultivator and air-seeder were found similar to those of rotary harrow and seeder in Van Muysen et al. (2002), which is a typical secondary tillage operation in central Belgium.

For the field site used in this study, one full tillage sequence (1-year) would normally consist of one pass of deep-tiller, two passes of spring-tooth-harrow and one pass of light-cultivator followed by one pass of air-seeder (LC/AS, not LC + AS). Translocation models for the implements were summed to establish a model for one full sequence by using Eq. (7) (Table 5). For one full sequence, α, β and γ values found in this study were about one half, one third and one fifth, respectively, of those found by Lobb and Kachanoski (1999b) in Ontario, Canada, indicating that tillage translocation in a cereal-based production system, which represents the predominant cropping system of the Canadian Prairies region, was considerably less intensive than in a conventional tilled corn-based production system in Canadian Great Lakes region.

3.9. Experiment errors

The unexplained variability in the regression data is a result of the inherent variation of tillage translocation and experiment errors. The major errors of this study might come from the sampling. The loss of tracer during sampling was one inevitable source of experiment errors. The further the tracer is translocated, the more difficult it is to find. The loss of tracer normally causes an under-estimation of tillage translocation. In this study, except for LC, the tracer recovery rate (RR) was quite high, an average of 98%, 98%, 97% and 90% for DT, SH, AS and LC/AS, respectively (Table 2). Errors due to the loss of tracer were considered to be very low. The lowest RR was found for LC (83%). A possible reason for this is the limited sampling time. Between the LC and AS, we had only 1 week to recover the tracers of the LC plots and to put another set of plots in place for the AS, so field activities were rushed. While after the seeding, we had plenty of time to recover the tracer of LC/AS, hence higher RR values. During sampling, even though a frame was set up as a reference, it was difficult sampling lengths of exactly 10 cm. When the soil is dry and loose, soil and tracer from the adjacent sampling slice might fall into the slice being sampled. Also, when sampling to greater depths it was difficult to cut each slice normal to the soil surface. Sampling length, which was supposed to be 10 cm, could vary at depth by up to 1 cm. However, such errors are compensatory, i.e. 1 cm longer on one slice results in 1 cm shorter in the adjacent slice, so that these errors will not affect the translocation estimates (T_P, T_L and T_M) but might cause under estimation of the translocation percentiles (λ_p).

Another source of experiment error is the topographic survey. In theory the accuracy of Total Station was adequate (less than 1 cm); however, in practice the accuracy may have been less than adequate. It has been found that slope gradient and slope curvature typically vary about ±5% and ±30%, respectively, when different survey points were used. Errors due to the surveyors and the surface roughness may contribute the most to these variations.

The tillage translocation calculation was based on the assumption that all plots were oriented perpendicular to tillage direction; however, it is very difficult to ensure that. Even with plots oriented to perpendicular to the intended path of tillage, the operation of the tillage implement does not follow exactly the intended path, a straight line. The plots deviated up to ±5° from perpendicular to the actual tillage direction. Assuming forward translocation exceeds lateral translocation, tillage translocation would be under estimated due to this error.

The summation curve method used in this study provides a parameter, ε, to evaluate the experiment error and the inherent variation of tillage translocation (Fig. 5). The ε value is not a direct measure of the errors but it indicates the level of the errors associated with the summation curve for different plots and different implements. In this study, for all the plots, the value of ε ranges from 0.1% to 37.4% and overall averages at 9.3% (Table 2). In general, the experiment errors were considered to be low. A Tukey–Kramer test showed that ε for AS is significantly greater than those for DT, LC and LC/AS with that for SH in between (Table 2). No significant difference was found between the Long Slope Area and the Bowl Area (data not shown). A test was conducted by averaging the first two samples' data (this will not change the estimated T_P and T_M values) and recalculating ε (data not shown). The overall average of the ε values dropped down to 1.8%. This indicates that the major contributor to ε is the variability of the data in the first two samples (within the original tracer-labeled region). This high variability is mainly due to the much deeper plot depth than the tillage depth and does not affect the accuracy of the estimated T_P and T_M values.

4. Conclusions

Tillage translocation was found to be highly variable for all the tillage implements. Regression analysis showed that there were significant relationships between tillage translocation and slope gradient. This confirmed slope gradient to be the predominant factor driving tillage translocation. Except for the light-cultivator, slope curvature was also found to have an effect on tillage translocation and, therefore, we recommend including slope curvature in the tillage translocation model as a secondary factor. For light-cultivator, though it is a secondary tillage implement, its dispersivity was greater than that of the deep-tiller, the primary tillage implement, but its erosivity was lower than that of the deep-tiller. The erosivity of air-seeder and spring-tooth-harrow were much lower than that of light-cultivator and deep-tiller, but their effects were not negligible, especially when they were conducted shortly after another tillage operation. The erosivity of air-seeder after one pass of light-cultivator was found comparable to the deep-tiller. For a full sequence, the erosivity of the tillage system in our study site was considerably lower than a traditional defined conventional tillage system (i.e. with a moldboard plough) indicating the considerably less intensive tillage system associated with the cereal-based production system in the Canadian Prairies. The different relationships between tillage translocation and slope gradient/slope curvature in the Long Slope Area and the Bowl Area suggested that landform type might also affect tillage translocation and different experiment design may be needed for different landform types.

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