Tillage erosion: a review of controlling factors and implications for soil quality

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Abstract: Tillage erosion has been identified as an important global soil degradation process that has to be accounted for when assessing the erosional impacts on soil productivity, environmental quality or landscape evolution. In this paper, we present a summary of available data describing tillage erosion. This provides insights in the controlling factors determining soil redistribution rates and patterns by tillage for various implements used in both mechanized and non-mechanized agriculture. Variations in tillage depth and tillage direction cause the largest variations in soil redistribution rates, although other factors, such as tillage speed and implement characteristics, also play an important role. In general, decreasing tillage depth and ploughing along the contour lines substantially reduce tillage erosion rates and can be considered as effective soil conservation strategies. Implement erosivities reported in literature, characterized by the tillage transport coefficient, are very consistent and range in the order of 400–800 kg $m^{-1}yr^{-1}$ and 70–260 kg $m^{-1}yr^{-1}$ for mechanized and non-mechanized agriculture, respectively. Comparison of tillage erosion rates with water erosion rates using a global data set indicates that tillage erosion rates are at least in the same order of magnitude or higher than water erosion rates, in almost all cases. Finally, we discuss how tillage erosion increases the spatial variability of soil properties and affects soil nutrient cycling. Considering the widespread use of tillage practices, the high redistribution rates associated with the process and its direct effect on soil properties, it is clear that tillage erosion should be considered in soil landscape studies.

Key words: soil erosion, soil quality, tillage erosion, ^{137}Cs.

I Introduction

Unlike water and wind erosion, whose effects are often dramatic and can be easily identified in the landscape, the extent and severity of tillage erosion only become apparent after several decades of tillage through variations in soil properties (the appearance of subsoil at the surface) and the development of tillage-related landforms like tillage banks. It is therefore no surprise that attention of soil erosion research during the last decades has focused heavily on sheet and rill erosion (Govers *et al.*, 1999). However, a large body of information, from a wide range of research domains, is available in literature that indicates that tillage is responsible for the movement of soil material. These papers focus on the investigation of tillage effects on (i) the dispersion of weed seeds (Marshall and Hopkins, 1990; Marshall and Brain, 1999), (ii) the incorporation of fertilizers or crop residues (Staricka *et al.*, 1990; 1991), (iii) the dispersion of soil amendments or constituents in long-term field experiments (Sibbesen *et al.*, 1985; 2000; Sibbesen and Andersen, 1985; Sibbesen, 1986), (iv) the redistribution of archaeological artefacts in agricultural land (Reynolds, 1988; Yorston *et al.*, 1990) or (v) on the design and performance of tillage implements (Reaves and Schafer, 1975; Kermis, 1978). Although these studies demonstrated the existence of substantial soil translocation by tillage operations, the identification of tillage erosion was hampered by the fact that they were conducted on level land, so that the assessment of tillage erosion rates and patterns was not possible.

Mech and Free (1942) were the first to carry out systematic tillage erosion experiments with tillage implements common for that time. They concluded that soil movement was far from insignificant and its intensity was related to slope gradient. Follow-up experiments by Petersen (1960) and by Weinblum and Stekelmacher (1963) corroborated these findings but were never published in international literature. In addition to this, a considerable amount of qualitative information on the importance of tillage erosion was published. This was mainly related to the formation of lynchets or soil banks (Papendick and Miller, 1977) and the development of terraces (Aase and Pikul, 1995). Other papers pointing to the importance of tillage erosion were: Dejong *et al.* (1983); Kachanoski *et al.* (1985); Revel and Guiresse (1995). Some authors relate the variability in crop yield and soil quality to the possible effects of tillage erosion. Miller *et al.* (1988) and Moulin *et al.* (1994) found a significantly lower soil organic matter content and crop yield on slope convexities. Also Verity and Anderson (1990) observed lower grain yields on upper convex slope positions.

Researchers working in relative isolation in eastern Europe have since long recognised soil tillage as an important erosion process on agricultural land (Khachatryan, 1985). Various experimental studies of tillage translocation and tillage erosion were made (Czyzyk, 1955; Kiburys, 1989; Martini, 2005), including investigations on terrace formation dynamics due to tillage (Lobotka, 1955).

The development of the ^{137}Cs technique has contributed significantly to the recognition of the tillage erosion process. The technique allows to assess the total soil redistribution rates and patterns in a landscape over a timescale of several decades, independent of the process causing it. Early studies whereby the ^{137}Cs technique was used showed a rather unexpected spatial pattern of soil erosion: highest soil losses occurred on convexities and deposition in hollows (eg, Dejong *et al.*, 1983; Quine and Walling, 1991). This spatial pattern did not agree with the pattern that can be expected to result from water erosion. Furthermore, comparison of ^{137}Cs derived erosion rates and patterns with results of water erosion models often showed poor agreement (Dejong *et al.*, 1986; Soileau *et al.*, 1990; Bernard and Laverdiere, 1992). Other studies supplied additional evidence that soil erosion occurred on unexpected locations on sloping agricultural land, eg, studies of soil profile truncation (eg, Daniels *et al.*, 1985; Verity and Anderson, 1990); of spatial variation in crop productivity (eg, Miller *et al.*, 1988; Cao *et al.*, 1994) or whereby elevation differences between agricultural land and adjacent non-cultivated land were used to assess soil erosion (Govers *et al.*, 1993).

It was only in the late 1980s (eg, Kiburys, 1989) and early 1990s (eg, Lindstrom *et al.*, 1992; Govers *et al.*, 1994; Lobb *et al.*, 1995) that systematic studies of tillage translocation and erosion were made. These experimental studies showed that tillage results in a net movement of soil, leading to a net soil loss (tillage erosion) from convex landscape positions and a net soil gain (tillage deposition) in concave landscape positions. Later, studies combining high-resolution ^{137}Cs data with geomorphological models (Govers *et al.*, 1996; Quine *et al.*, 1997) and additional tillage erosion experiments (eg, Guiresse and Revel, 1995; Poesen *et al.*, 1997; Lobb *et al.*, 1999; Van Muysen *et al.*, 1999; Montgomery *et al.*, 1999; Quine *et al.*, 1999a) provided further evidence for substantial tillage induced soil erosion and deposition under mechanized agriculture.

At present, there are over 80 research papers in the literature that specifically deal with tillage erosion (Figure 1). Initially, these studies focused on the experimental identification of controlling variables and the assessment of tillage erosion rates (mostly using ^{137}Cs as a marker of soil movement). More recently, tillage erosion effects on soil quality and productivity in various agro-ecological environments have been documented (Li and Lindstrom, 2001; Kosmas *et al.*, 2001; de Alba, 2001; Quine and Zhang, 2002; da Silva and Alexandre, 2004; Li *et al.*, 2004; Heckrath *et al.*, 2005) and tillage erosion simulation models have been developed (Govers *et al.*, 1996; Van Oost *et al.*, 2000b; 2003b; de Alba, 2003; Schoorl *et al.*, 2004; Quine and Zhang, 2004c). While early studies on tillage erosion strongly focused on mechanized agriculture, recent studies have shown that substantial tillage erosion also occurs in developing countries with animal or man powered tillage tools, especially when tillage is performed in dissected landscapes on steep slopes (Kimaro *et al.*, 2005; Turkelboom *et al.*, 1997; 1999; Thapa *et al.*, 1999a; 1999b; Quine *et al.*, 1999b; 1999c; Nyssen *et al.*, 2000; Dercon *et al.*, 2003; Zhang *et al.*, 2004b). Consequently, tillage erosion is now recognized as an important global soil degradation process that has to be accounted for when assessing the erosional impacts on soil productivity (eg, Heckrath *et al.*, 2005), environmental

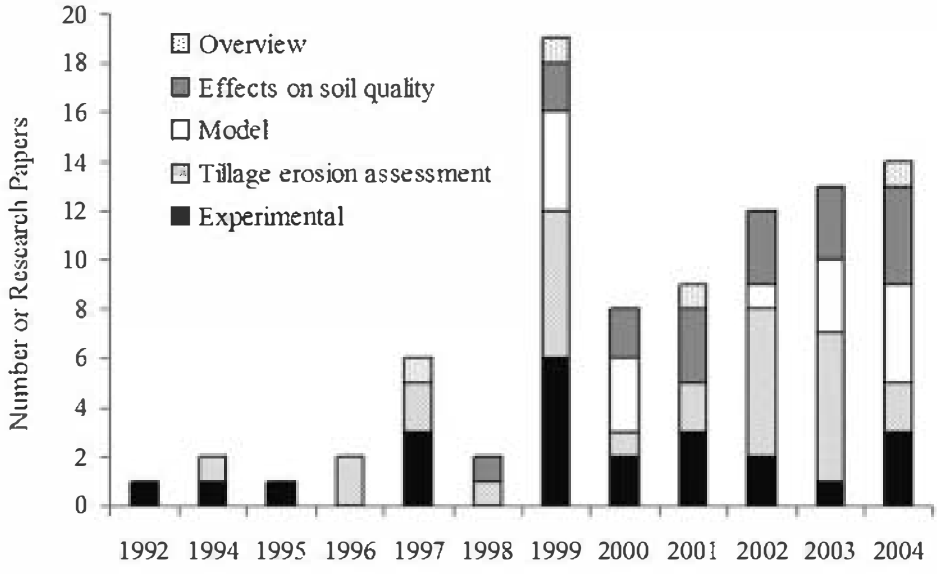

Figure 1 Temporal evolution and typology of tillage erosion research papers in literature
Source: Web of Science.

quality (eg, Lal, 2001) or landscape evolution (eg, Quine *et al.*, 1997).

Although a large body of information on tillage erosion is now available, attempts to identify the major controls on the process and to quantify the importance of tillage erosion in the total soil redistribution on arable lands are very rare. This article presents the principles of tillage erosion, reviews estimates of controlling variables, describes strategies and practical considerations in soil conservation strategies, and assesses the overall importance of tillage erosion.

II The principle of tillage erosion

1 Definition

Whenever soil is cultivated, tillage translocation, which is the displacement of the cultivation layer, takes place. This translocation is expressed as mass of soil moved by tillage in a specific direction per meter width. Translocation can also be expressed as a depth-averaged length, ie, the distance the till-layer is translocated. Experimental studies have shown that slope gradient has a dominant influence on soil translocation during tillage operations, as it is a gravity-driven process (Lindstrom *et al.*, 1992; Govers *et al.*, 1994; Lobb *et al.*, 1995; Poesen *et al.*, 1997; Van Muysen *et al.*, 1999; Quine *et al.*, 1999a). The basic nature of this process is illustrated in Figure 2. Generally, soil translocation rates are highest when tillage is performed in the downslope direction on steep slopes. Translocation rates decrease gradually when moving to less steep slopes and are lowest when tillage is performed in the upslope direction on steep slopes. Consequently,

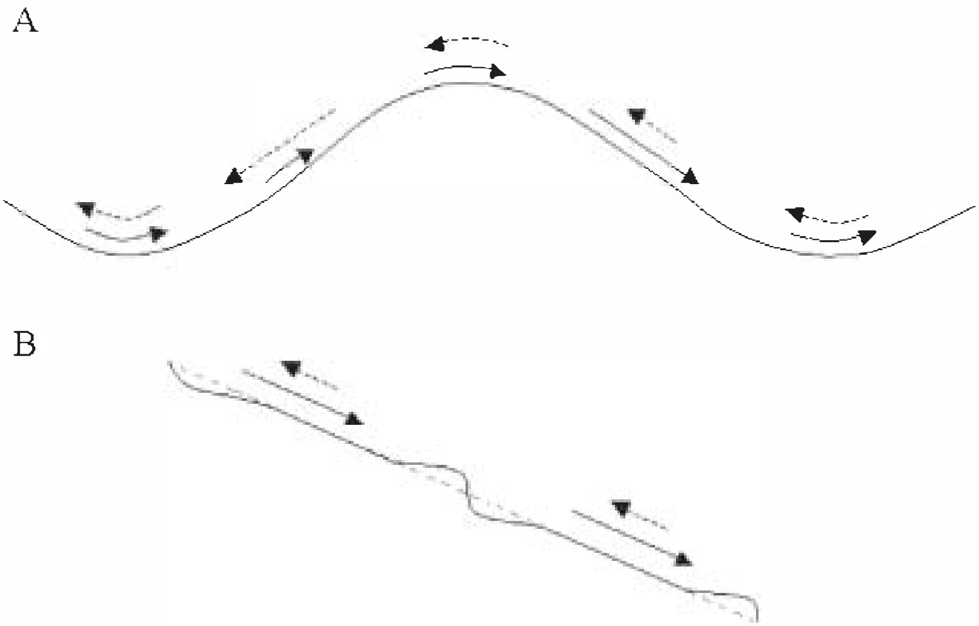

Figure 2 Principle of tillage erosion. (A) Variability of soil translocation in a hilly landscape. Soil translocation by tillage will result in soil loss on convex slope positions because there is an increase in slope gradient. Conversely, deposition takes place in concave slope positions. (B) In dissected landscapes (field boundaries, grass strips, terraces), tillage leads to soil loss on the uppermost portion of the slope segment and deposition occurs in lower portions, leading to the formation of soil banks. The lengths of the arrows reflect the magnitude of the process

soil translocation by tillage varies within landscapes and a net movement of soil occurs on sloping land. For example, the downslope soil movement after a downslope tillage operation, is not fully compensated for by complementary upslope tillage operation, leading to a net downslope movement of soil.

Various definitions for tillage erosion are given in literature. Lindstrom *et al.* (2001) define it as 'the net movement of soil downslope through the action of mechanical implements'; while Lobb *et al.* (1999) use the definition 'the net downslope translocation of soil material by tillage'. Lobb *et al.* (1995) provide a broad definition: 'the loss and accumulation of soil resulting from the variable translocation of soil by tillage'. Here, both component of the erosion process, ie, the erosion of soil material at specific landscape positions (tillage erosion) as well as the subsequent deposition of this eroded material at other positions (tillage deposition), are explicitly denoted.

2 *Patterns and field evidence of tillage erosion*

Soil translocation by tillage will result in soil loss on convex slope positions such as crests and shoulder slopes because there is an increase in slope gradient, thus an increase in soil translocation rate. Conversely, soil deposition will take place in concave slope positions. The spatial signatures of tillage erosion differ fundamentally from those of water erosion: soil loss by tillage will be most intense on landscape positions where water erosion is minimal (ie, on convexities and near upslope field boundaries) while areas of soil accumulation by tillage are often areas where water erosion is maximal (ie, hollows) (see Figure 3 for illustration). This has also implications for contemporary landform evolution on agricultural land: while continuing water erosion leads to increased incisions in concavities and a gradual increase in slope angle on convex slopes, tillage erosion will smoothen the landscape and reduce slope angles by moving soil from convexities to concavities.

Tillage erosion can be evidenced from differences in soil properties along a hillslope. Intensive tillage erosion results in substantial soil truncation and within field redistribution of soil and soil constituents. Continuing removal of topsoil and the subsequent lowering of the plough layer on convexities lead to the incorporation of nutrient-depleted subsoil material in the plough layer. At the same time, tillage accumulates soil at concavities where a deep soil enriched in nutrients develops. In areas with undulating topography, the appearance of subsoil material is indicative for tillage erosion (Figure 4).

Field boundaries represent physical barriers that interrupt soil flux by tillage (Papendick and Miller, 1977; Dabney *et al.*, 1999; Van Oost *et al.*, 2000a). These lines of zero flux produce a net soil accumulation on the upslope side or a net soil loss on the lower slope side. When a cross-slope boundary between fields is located at mid-slope positions, opposite balances of net soil loss or soil gain take place on the two sides of the boundary with the consequent formation of a linear step, ie, lynchet or soil bank, along the boundary. The formation of soil banks due to tillage erosion is illustrated in Figure 5. Two types of tillage erosion should therefore be considered when analysing tillage erosion rates: (i) tillage erosion due to a change in slope (topography-based tillage erosion) and (ii) tillage erosion due to the effect of field boundaries (field boundary tillage erosion). It is clear that field boundary tillage erosion is important in dissected landscapes where tillage is conducted on small fields (eg, terrace agriculture in mountainous areas (Dercon *et al.*, 2003), whereas topographical tillage erosion is likely to be dominant in areas of mechanized agriculture which are associated with large fields (Van Oost *et al.*, 2000a).

3 *Equations describing tillage translocation and erosion*

The most widespread used tillage model in experimental and modelling studies is based

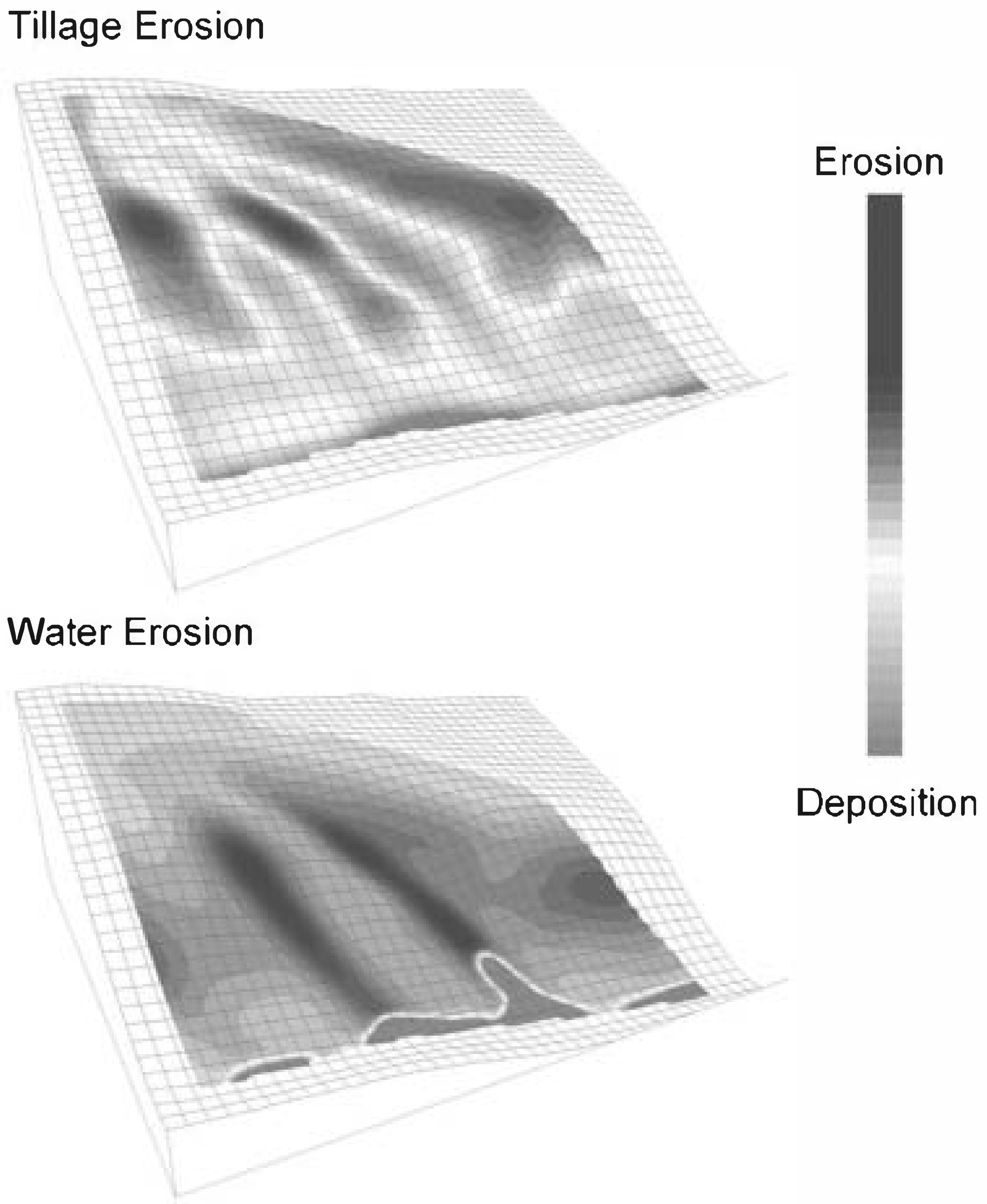

Figure 3 Typical spatial patterns of tillage and water erosion simulated with the WaTEM model (Van Oost *et al.*, 2000a). Cell size is 6 × 6 m. Height difference between top and bottom of the field is approximately 12 m

on the model proposed by Govers *et al.* (1994). Here, tillage erosion is considered as a diffusion type process using the following reasoning. The rate of soil translocation in the direction of tillage, Q_s ($kg\,m^{-1}$), can be calculated as:

$$Q_s = \rho_b \bar{d} D \qquad (1)$$

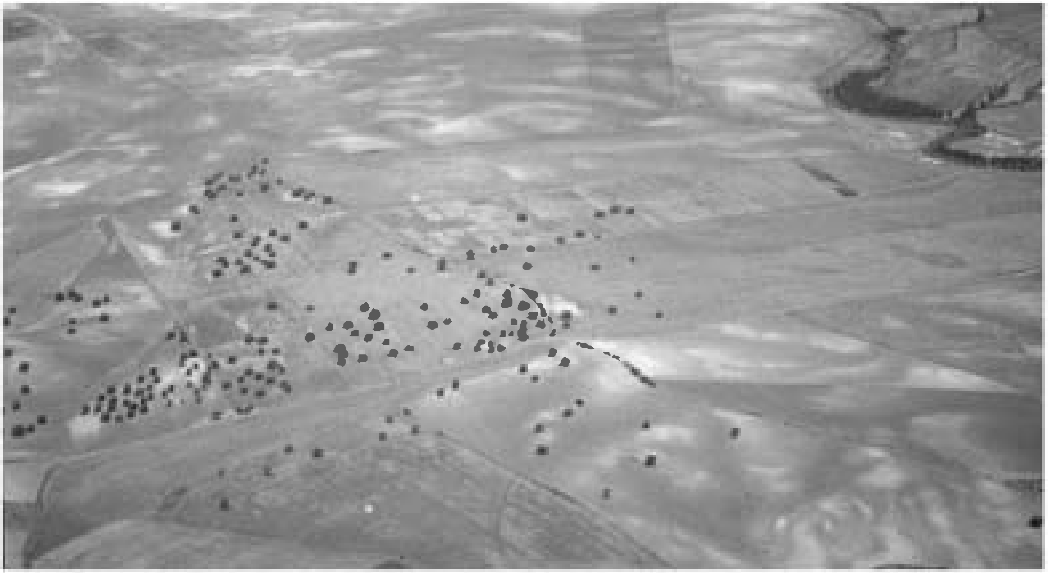

Figure 4 Typical spatial variability of soils in agricultural landscapes of rolling topography. In the picture, truncated soil profiles (of clear colour due to the presence of calcic material from an original subsurface soil horizon) are predominant in the upper part of slopes and convexities and are indicative for tillage erosion (Castilla-La Mancha, Central Spain)

Figure 5 Field boundaries represent a physical barrier for soil transport by tillage. Soil accumulates at the upslope side while severe truncation takes place at the downslope side, leading to the formation of soil banks. The soil banks in the picture are up to 1.6 m in height (Castilla-La Mancha, Central Spain)

where ρ_b is the soil bulk density (kg m^{-3}), $\bar{d}$ is the average soil translocation distance in the direction of tillage (m), and D is the tillage depth (m). Tillage experiments have found mean translocation distances as a result of a single tillage operation to be linearly, and inversely, related to slope (Govers *et al.*, 1994):

$$\bar{d} = a + bS \tag{2}$$

where S is the slope tangent (positive upslope; negative downslope), and a and b are regression constants. Assuming opposing directions in successive tillage operations and that uphill slopes are designated as positive slope and downhill slopes are designated as negative slopes, the average net downslope soil translocation $\bar{d}_n$ per tillage operation may be expressed as

$$\bar{d}_n = \frac{(a + bS) - (a - bS)}{2} = bS \tag{3}$$

and the net downslope rate of soil translocation after the two tillage operations will be:

$$Q_{t,n} = D\rho_b bS \tag{4}$$

Using the continuity equation for sediment movement on a hillslope and assuming the x-axis to be positively oriented in the downslope direction, the tillage erosion or accumulation rate may then be written as:

$$E = -\frac{\partial Q_t}{\partial x} = -D\rho_b b\frac{\partial h}{\partial x} = k_{til}\frac{\partial^2 h}{\partial x^2} \tag{5}$$

where h is the height at a given point of the hillslope and $k_{til}(= -D\rho_b b)$ is a constant. This means that the rate of tillage erosion may be characterized by (i) a proportionality factor, k_{til}, which is referred to as the tillage transport coefficient, and (ii) the rate of change in slope in the direction of tillage. The tillage transport coefficient is an expression of tillage erosivity and permits the comparison of different tillage implements.

It is important to note that this diffusion-type model of tillage translocation and erosion is limited by the following necessary assumptions: (i) tillage depth and soil bulk density do not vary in space, (ii) tillage soil translocation can be expressed as a linear, univariate function of the slope gradient and (iii) tillage is conducted in opposing directions. However, the latter assumption is not necessary when estimating topography-based tillage erosion. In this case, the tillage transport coefficient is independent of the tillage direction applied, ie, it can be used to estimate erosion rates for alternating up- and downslope tillage operations or consecutive up- or downslope operations.

III Factors controlling tillage translocation and erosion

The process of tillage erosion can be seen as a function of the erosivity of a given tillage operation (T_E) and the erodibility of the cultivated landscape (L_E) (Lobb *et al.*, 1999):

$$E_t \approx f(T_E, L_E) \tag{6}$$

where E_t is the tillage erosion rate, resulting from a specific tillage operation. This general concept is illustrated in Figure 6. Tillage erosivity, T_E, the potential for a given tillage event to erode soil within a landscape, is a function of several physical and human parameters. These include implement characteristics (I_m), (eg, tool shape, width, length), operational parameters (I_o) (eg, tillage depth, speed, tillage direction), the responsiveness of the tillage operator to changing landscape and soil conditions (I_r) (eg, manual depth adjustment to compensate for power requirement shortage).

$$E_T \approx f(I_m, I_o, I_r) \tag{7}$$

Landscape erodibility L_E is the propensity of a landscape to be eroded by tillage, and is determined by topographical parameters (I_t) (eg, slope gradient, curvature); field parameters (I_f) (eg, field size and shape) and physical properties of the soil (I_s) (eg, soil texture, soil moisture content, the soil's resistance to displacement by tillage):

$$E_L \approx f(I_t, I_f, I_s) \tag{8}$$

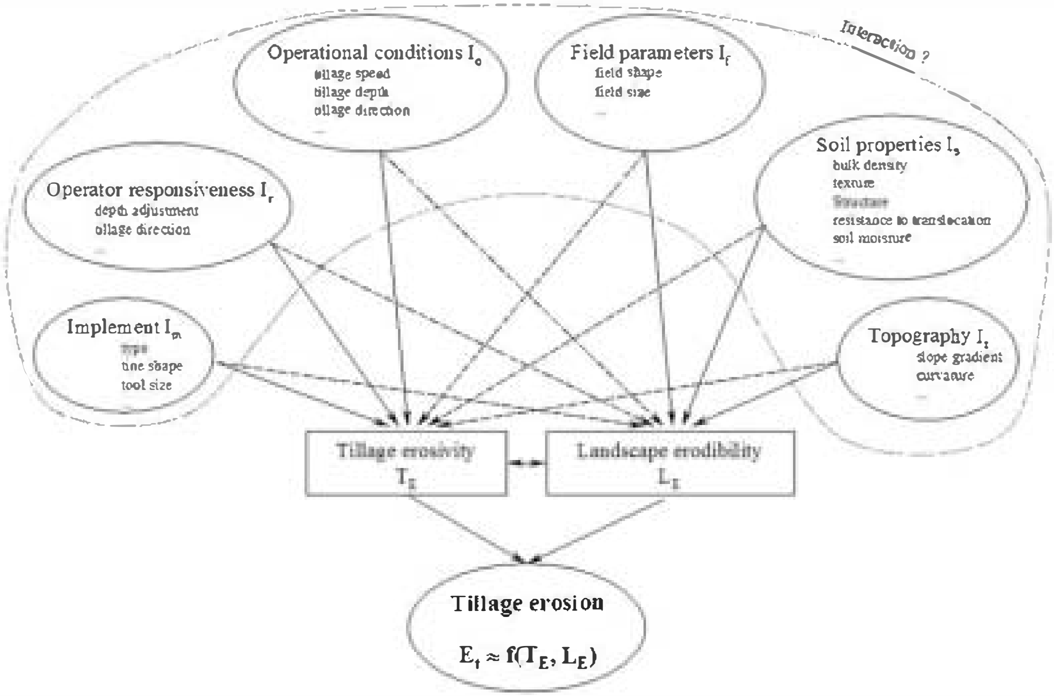

Figure 6 Factors of tillage erosion

It is evident that these factors interact. For example, each tillage implement has a recommended depth and speed of operation. Deviations from these values may occur, both in response to changing power requirement and availability, as well as to spatial variations in soil properties, especially in complex topography. This will not only affect the implement performance, but it may also influence tillage translocation and, consequently tillage erosion. Similarly, the tillage direction applied is decided upon by the farmer, based on information on field size and shape in combination with topographical characteristics.

As landscape erodibility is a static variable which is difficult to control, most soil conservation studies focus on the variables reducing tillage erosivity. In the following section, experimental derived tillage transport coefficients reported in literature will be used to assess tillage erosivity in terms of implement and operational characteristics for two categories of tillage implements, ie, mouldboard and chisel/cultivator. In addition, the tillage erosivity of secondary tillage operations and animal/man-powered tools are discussed.

1 *Mouldboard tillage*

Mouldboard tillage is the standard primary tillage technique in many agricultural systems and is therefore the most studied implement in tillage erosion experiments. Mouldboard tillage is essentially a two-dimensional process characterized by a displacement component in the tillage and one perpendicular to tillage direction (turning direction). Two types of mouldboard tillage experiments can be identified: (i) experiments conducted parallel to the steepest gradient (up- and downslope tillage, UD) where only the translocation in the tillage direction is considered and (ii) experiments along the contour (contour tillage, C) where only translocation in the turning direction is considered.

Table 1 Comparison of tillage transport coefficient (k_{til}), available in or calculated from the literature for mouldboard tillage

Source	Country	Tillage speed V ($km\,h^{-1}$)	Tillage depth D (m)	Bulk density ρ_b ($kg\,m^{-3}$)	k_{til} ($kg\,m^{-1}$ per operation)	Tillage direction*
Lindstrom *et al.*, 1992	USA	7.6	0.24	1350	363	C
Van Muysen *et al.*, 2002	Belgium	4.9	0.26	1540	184	C
St Gerontidis *et al.*, 2001	Greece	4.5	0.2	1420	134	C
St Gerontidis *et al.*, 2001	Greece	4.5	0.3	1420	252	C
St Gerontidis *et al.*, 2001	Greece	4.5	0.4	1420	360	C
de Alba, 2001	Spain	4.5	0.24	1370	164	C
Heckrath *et al.*, 2006	Denmark	4.9	0.23	1529	49	C
Heckrath *et al.*, 2006	Denmark	4.0	0.26	1490	132	C
Petersen, 1960	USA	3.6	0.16	1239	64	C
Montgomery *et al.*, 1999	USA	3.6	0.23	1310	109	C
Heckrath *et al.*, 2006	Denmark	4.9	0.24	1555	281	S
Heckrath *et al.*, 2006	Denmark	4.1	0.24	1449	239	S
Heckrath *et al.*, 2006	Denmark	4.1	0.22	1423	137	S
Quine *et al.*, 2003	New Zealand	7.0	0.17	1350	324	UD
Lindstrom *et al.*, 1992	USA	7.6	0.24	1350	330	UD
Govers *et al.*, 1994	Belgium	4.5	0.28	1350	234	UD
Van Muysen *et al.*, 1999	Spain	1.8	0.33	1070	245	UD
Van Muysen *et al.*, 1999	Spain	2.7	0.15	1650	85	UD
Van Muysen *et al.*, 2002	Belgium	5	0.25	1500	224	UD
Van Muysen *et al.*, 2002	Belgium	5.4	0.21	1560	169	UD
Lobb *et al.*, 1995	Canada	4	0.15	1350	184	UD
Lobb *et al.*, 1999	Canada	6.2	0.23	1350	346	UD
Revel and Guiresse, 1995	France	6.5	0.27	1350	263	UD
Mech and Free, 1942	USA	3.6	0.08	1155	24	UD
St Gerontidis *et al.*, 2001	Greece	4.5	0.2	1420	153	UD
St Gerontidis *et al.*, 2001	Greece	4.5	0.3	1420	383	UD
St Gerontidis *et al.*, 2001	Greece	4.5	0.4	1420	670	UD
de Alba, 2001	Spain	4.5	0.24	1370	204	UD
Heckrath *et al.*, 2006	Denmark	4.9	0.25	1517	200	UD
Heckrath *et al.*, 2006	Denmark	6.3	0.26	1507	335	UD
da Silva *et al.*, 2004	Portugal	3.7	0.39	1680	770	UD
Quine and Zhang, 2004b	UK	5.9	0.21	1374	101	UD
Kosmas *et al.*, 2001	Greece	4.5	0.18	1598	63	UD
Kosmas *et al.*, 2001	Greece	4.5	0.25	1598	159.8	UD

* Tillage direction: contour (C), slantwise (S), up and down (UD)

In Table 1, the results of 34 mouldboard tillage experiments are listed with their operational characteristics and tillage transport coefficient. 24 experiments were performed under up- and downslope (or slantwise) tillage while 10 are contour tillage experiments. The experiments exhibit a wide range in tillage speed (range 1.4–7.6 $km\,h^{-1}$) and tillage depth (range 0.08–0.4 m). Although these studies report only average values for the tillage speed and depth applied during the experiment, they provide a valuable basis for assessing the operational effects on mouldboard tillage erosivity. We used a non-linear regression of the form:

$$k_{til} = a\rho_b D^{\alpha} V^{\beta} \qquad (9)$$

A similar approach has previously been used by (Van Muysen *et al.*, 2002). Equation (9) is capable of predicting the trends observed in the published data ($r^2 = 0.67$; $P < 0.0001$) (Figure 7a and Table 5). The regression analysis indicates that tillage erosivity largely depends on tillage depth while the effect of tillage speed is less pronounced. However,

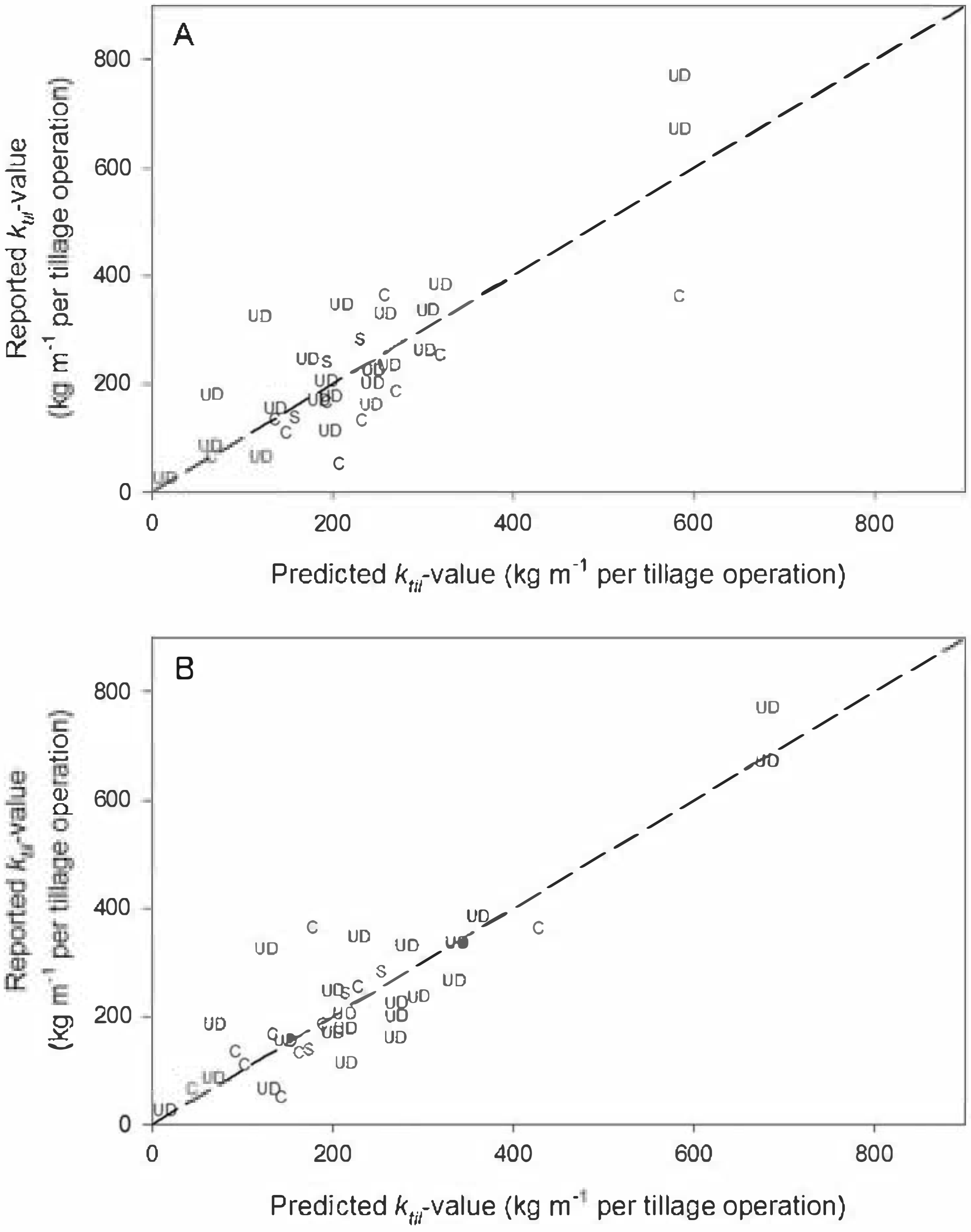

Figure 7 Relationship between predicted tillage transport coefficient and reported k_{til} values for data sets on mouldboard tillage for up- and downslope tillage (UD) and contour tillage (C) using (A) equation 9 and (B) equation 10

the inclusion of a dummy variable to account for the direction of tillage, that is:

$$k_{til} = a\rho_b D^{\alpha} V^{\beta} T^{\gamma} \qquad (10)$$

where T equals 1 for contour tillage and 2 for up- and downslope tillage, considerably improved the regression ($r^2 = 0.79$; $P < 0.0001$) (Figure 7b and Table 5).

Figure 8 shows the tillage transport coefficients for up- and downslope and contour tillage for different values of tillage speed and depth based on this statistical model. Tillage depth is the most important factor. For example, the $k_{til,UD}$-value increases with 141% if tillage depth changes from 0.2 to 0.3 m ($V = 4\,\mathrm{km\,h^{-1}}$). This effect corroborates findings by Van Muysen *et al.* (2002), St Gerontidis *et al.* (2001) and Heckrath *et al.* (2006), reporting values for α between 1 and 2. The effect of tillage depth on mouldboard erosivity can be explained as follows: tillage erosion rates, and consequently tillage erosivity, increase linearly with tillage depth as more soil is subject to transport (see equation 5). The additional increase in mouldboard erosivity is related to the larger volume soil occupies after ploughing. Gravitational forces amplify the spreading of this larger volume of soil during downslope tillage while the spreading is hampered during upslope tillage. Tillage speed also increases mouldboard erosivity but to a lesser extent. For example, the $k_{til,UD}$-value increases with only 20% if tillage speed changes from 3 to $4\,\mathrm{km\,h^{-1}}$ ($D = 0.25\,\mathrm{m}$). Van Muysen *et al.* (2002) and Heckrath *et al.* (2006) reported values between 0.39 and 0.96 for β, which is comparable to the value of 0.6 derived here.

This analysis shows that tillage direction has an important control on mouldboard erosivity. The value of 0.71 for γ means that the ratio between k_{til}-values for up- and downslope ($k_{til,UD}$) tillage and contour tillage ($k_{til,C}$) is 1.64, or that up- and downslope mouldboard tillage is more erosive than contour tillage. Experimental studies where contour and up- and downslope tillage were directly compared report similar ratios of 1.22 (Van Muysen *et al.*, 2002), 1.14–1.86 (St Gerontidis *et al.*, 2001) and 1.24 (De Alba, 2001). In contrast, Lindstrom *et al.* (1992) found that contour tillage was slightly more erosive than up- and downslope tillage (ratio 0.91).

The differential behaviour in soil translocation dynamics for contour and up- and downslope tillage strongly suggests that a 1-dimensional analysis of soil translocation, where slope gradient only varies in a single direction, is not applicable in real 2-dimensional landscapes. Mouldboard tillage is characterized by a displacement component in the tillage and turning direction and each of these can be affected by the slope in the tillage and turning direction. De Alba (2001), Quine and Zhang (2004a) and Heckrath *et al.* (2006) showed that the simultaneous change of slope gradients in both tillage and turning direction may exert an import influence on mouldboard erosivity. These are important findings as under normal agricultural practice on hummocky terrain simultaneously changing slope gradients in tillage and turning direction will be rather common as field geometry, more than topography, determines the tillage direction. Heckrath *et al.* (2006) presented the first study where the effect of simultaneously changing slope gradients in tillage and turning direction were investigated. They concluded that contour tillage was the least erosive, followed by slantwise tillage turning the soil upslope ($k_{til} = 110\,\mathrm{kg\,m^{-1}}$) while up- and downslope tillage was considered to be the most erosive ($k_{til} = 180$–$210\,\mathrm{kg\,m^{-1}}$).

2 *Chisel tillage*

In contrast with mouldboard tillage, relatively few tillage erosion studies report on chisel experiments and the variables controlling chisel erosivity are scarcely studied. In Table 2, all available experimental data is summarized. Although the typical working depth of a chisel operation is smaller than mouldboard operations, k_{til} values reported are only slightly lower than those for mouldboard tillage. The observed k_{til} values could be described by a model regression similar to

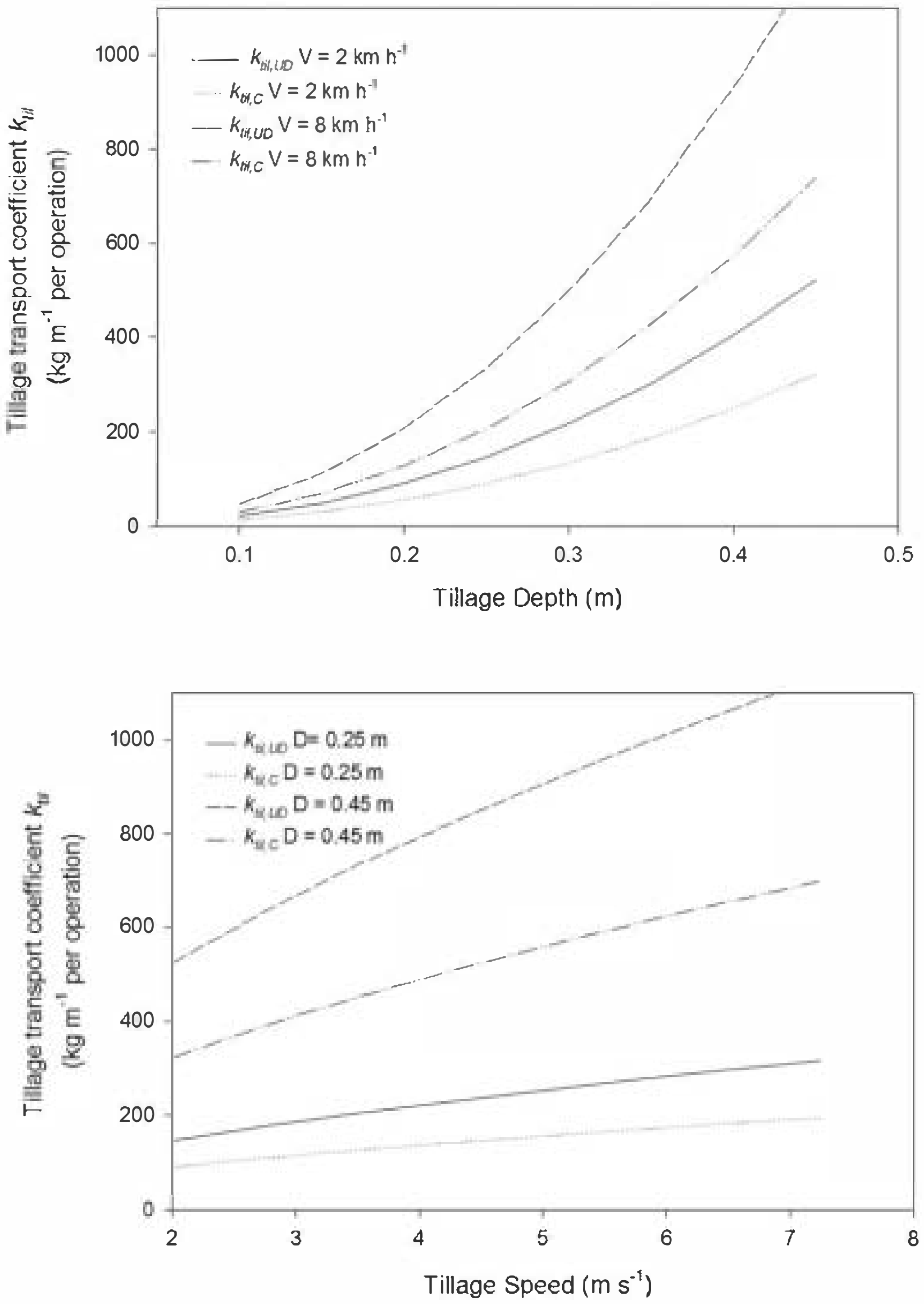

Figure 8 Mouldboard erosivity of up- and downslope ($k_{til,Up}$) and contour tillage ($k_{til,C}$) for different tillage speed and depth combinations

Table 2 Comparison of tillage transport coefficient (k_{til}), available in or calculated from the literature for chisel tillage

Source	Country	Tillage speed V ($km\,h^{-1}$)	Tillage depth D (m)	Bulk density ρ_b ($kg\,m^{-3}$)	k_{til} ($kg\,m^{-1}$ per operation)
Van Muysen *et al.*, 2000	Belgium	5.8	0.15	1560	225
Van Muysen *et al.*, 2000	Belgium	7.2	0.2	1250	545
Poesen *et al.*, 1997	Spain	2.3	0.16	1582	282
Poesen *et al.*, 1997	Spain	2.3	0.14	1582	139
Govers *et al.*, 1994	Belgium	4.5	0.15	1350	111
Lobb *et al.*, 1999	Canada	9.6	0.17	1580	275
Mech and Free, 1942	USA	3.6	0.06	1155	13
Quine *et al.*, 1999a	Spain	2.2	0.19	1371	657
da Silva *et al.*, 2004	Portugal	3.6	0.11	1600	75
da Silva *et al.*, 2004	Portugal	3.4	0.19	1600	27

equation (9) (Table 3, $r^2 = 0.89$, $p = 0.005$). Tillage depth strongly affects tillage erosivity while the effect of tillage speed was not significant. This sharply contrasts with the findings of Van Muysen *et al.* (2000). Using the results of a chisel experiment where speed and depth were varied, they suggested that chisel erosivity increases almost linearly with tillage speed and depth. However, it is evident that the model parameters derived here are based on a rather limited data set covering a wide range of soil conditions and chisel implements. It is likely that most of the observed variability is related to implement characteristics. Studies reporting high chisel k_{til} values (Poesen *et al.*, 1997; Quine *et al.*, 1999a) were conducted with a duckfoot chisel at very low speeds. Van Muysen *et al.* (2000) suggested that the wide tines used on a duckfoot chisel were responsible for the high translocation rates observed by Poesen *et al.* (1997) and Quine *et al.* (1999a). Typically, the implement coverage for a duckfoot chisel is *c.* 3 times higher than a chisel plough. It is clear that further experimental research is needed to assess the factors controlling chisel erosivity.

Table 3 Summary of results from regression analysis for mouldboard, chisel and non-mechanized tillage implements

	a	α	β	γ	r^2
Mouldboard					
$k_{til} = a\rho_b D^{\alpha} V^{\beta}$ (n = 34)	1.17 ($p = 0.027$)	2.10 ($p < 0.001$)	0.58 ($p = 0.065$)	–	0.67 ($p < 0.001$)
$k_{til} = a\rho_b D^{\alpha} V^{\beta} T^{\gamma}$ (n = 34)	0.97 ($p = 0.008$)	2.21 ($p < 0.001$)	0.57 ($p = 0.027$)	0.67 ($p = 0.0015$)	0.78 ($p < 0.001$)
Chisel					
$k_{til} = a\rho_b D^{\alpha}$ (n = 6)	1157 ($p = 0.52$)	4.84 ($p = 0.005$)	–	–	0.89 ($p = 0.005$)
Non-mechanized					
$k_{til} = a\rho_b D^{\alpha}$ (n = 7)	0.358 ($p = 0.06$)	0.71 ($p = 0.03$)	–	–	0.68 ($p = 0.02$)

p denotes statistical significance

3 Secondary tillage operations

Although mouldboard and chisel plough tillage make up the major part of an annual sequence of tillage operations under mechanized agriculture, they do generally not result in a surface that is smooth enough for seeding or planting. In many cases, mouldboard and chisel tillage is followed by harrowing or discing to reduce clod size and surface smoothening before seeding is carried out. In Table 4, k_{til} values for harrow, cultivator and disc implements are shown. Tillage erosivity for harrow and cultivator tillage is significantly lower than mouldboard and chisel tillage. In contrast, da Silva *et al.* (2004) and Lobb *et al.* (1999) report very high values for disc implements. da Silva *et al.* (2004) found that tillage depth, and to a lesser extent tillage speed and disc characteristics, had a major influence on disc erosivity.

4 Animal- and man-powered tillage tools

Only recently studies addressed tillage erosion by animal and man-powered tillage tools, which are common in present-day farming systems in developing countries. Lewis and Nyamulinda (1996), Turkelboom *et al.* (1997) and Zhang *et al.* (2004a; 2004b) demonstrated that manual tillage on steep slopes leads to significant downslope movement of soil. Rymshaw *et al.* (1997), Thapa *et al.* (1999a; 1999b), Quine *et al.* (1999b) and Nyssen *et al.* (2000) pointed out that shallow mouldboard or ard ploughing using animal traction can be very erosive. Table 5 summarizes all available tillage transport coefficients for animal- and man-powered tillage tools. The tillage transport coefficients are much lower than those associated with mechanized tillage operations and range between 30 and 250 kg m^{-1} per operation (compare with Table 1). This must be attributed to the typically lower tillage speeds and working depths associated with man- and animal-powered tillage tools as well as substantially different implement characteristics. Thapa *et al.* (1999a) compared up- and downslope tillage and contour tillage with an animal-powered mouldboard. They concluded that up- and downslope tillage with an animal-powered tool was 1.27 times more erosive than contour tillage, which is in the same order of magnitude as the ratios observed for mechanized mouldboard tillage.

5 Crop rotation tillage transport coefficients

In most agricultural systems, multiple tillage operations with different implements are required for crop cultivation. It is therefore useful not to express tillage erosivity on an implement basis, but to consider the erosivity of a typical sequence of tillage operations associated with a specific cropping system.

Table 4 Comparison of tillage transport coefficient (k_{til}), available in or calculated from the literature for secondary tillage operations

Source	Country	Tillage speed V (km h^{-1})	Tillage depth D (m)	Bulk density ρ_b (kg m^{-3})	k_{til} (kg m^{-1} per operation)	Implement
Lobb *et al.*, 1999	Canada	6.9	0.15	1580	13	cultivator
Mech and Free, 1942	USA	n.a.	0.08	n.a.	28	cultivator
Mech and Free, 1942	USA	n.a.	0.12	n.a.	78	harrow
Van Muysen and Govers, 2002	Belgium	6.8	0.07	1130	123	rotary harrow and seeder
da Silva *et al.*, 2004	Portugal	5.3	0.07	1650	9–333	harrow disc
da Silva *et al.*, 2004	Portugal	2.9	0.08	1178	18–770	harrow disc
Lobb *et al.*, 1999	Canada	3.0	0.17	1580	369	tandem disc

n.a.: data not available

Table 5 : Comparison of tillage transport coefficient (k_{til}), available in or calculated from the literature for non-mechanized agriculture

Source	Country	Tillage speed V (km h^{-1})	Tillage depth D (m)	Bulk density ρ_b (kg m^{-3})	k_{til} (kg m^{-1} per operation)	Tillage direction*
Nyssen *et al.*, 2000	Ethiopia	1.1	0.08	1143	68[a]	C
Thapa *et al.*, 1999a	Philippines	n.a.	0.2	730	76[a]	C
Quine *et al.*, 1999c	China	n.a.	0.17	1300	31	C
Thapa *et al.*, 1999b	Philippines	n.a.	0.2	1000	119[a]	C
Dercon *et al.*, unpublished data	Ecuador	n.a.	0.13	1203	83[a]	C
Rymshaw *et al.*, 1997	Venezuela	n.a.	0.2	1270	29[a]	C
Thapa *et al.*, 1999b	Philippines	n.a.	0.2	1000	152[a]	UD
Quine *et al.*, 1999c	China	n.a.	0.17	1300	250	UD
Turkelboom *et al.*, 1999	Thailand	n.a.	0.085	1100	77[m]	UD
Zhang *et al.*, 2004b	China	n.a.	0.22	1310	141[m]	UD
Kimaro *et al.*, 2005	Tanzania	n.a.	0.05	1200	84–108[m]	UD

[a] Animal-powered tillage; [m] manual tillage
Tillage direction: contour (C), slantwise (S), up and down (UD)
n.a.: data not available

Lobb *et al.* (1995) reported on the results of a series of tillage erosion experiments in Canada whereby the erosivity of a sequence of conventional tillage operations (1 mouldboard pass, 2 tandem disc passes and 1 tine cultivator pass) was studied. The tillage transport coefficient for this sequence was estimated as 473–734 kg m^{-1}. Van Muysen *et al.* (2006) studied a typical tillage sequence for mechanized agriculture, including multiple mouldboard, chisel and harrow passes, during a period of three years. These authors derived a tillage transport coefficient of 781 kg m^{-1}yr^{-1}, which is in good agreement with data reported in literature. This study also showed that the tillage transport coefficient of a sequence of tillage operations can be reasonably well predicted by summing the transport coefficients obtained from controlled, single pass experiments.

Crop rotation tillage transport coefficients can also be derived from ^{137}Cs data. This technique uses present-day ^{137}Cs inventories to optimize the parameters of spatially distributed soil erosion-deposition models that take into account all relevant processes (ie, water erosion, tillage erosion, and soil loss due to crop harvesting), so that the observed ^{137}Cs redistribution pattern is predicted as accurately as possible (Govers *et al.*, 1996; Quine *et al.*, 1997; Quine, 1999; Schuller *et al.*, 2003; Van Oost *et al.*, 2003a; Schoorl *et al.*, 2004). Table 6 presents the k_{til} values derived from ^{137}Cs data. The clearest characteristic of the data is the high degree of similarity in the k_{til} values for mechanized agriculture, ranging

Table 6 Long-term tillage transport coefficients inferred from ^{137}Cs data

Source	Country	k_{til} value (kg m^{-1}yr^{-1})
Mechanized agriculture		
Govers *et al.*, 1996	UK	397
Govers *et al.*, 1996	UK	348
Van Oost *et al.*, 2003a	Belgium	523
Quine *et al.*, 1996	UK	300
Quine *et al.*, 1994	Belgium	550
Heckrath *et al.*, 2005	Denmark	456
Non-mechanized agriculture		
Quine *et al.*, 1999b	China	108
Quine *et al.*, 1999b	Lesotho	243
Quine *et al.*, 1999b	Zimbabwe	113
Quine *et al.*, 1997	China	20–40

between 350 and 550 kg m^{-1} year^{-1}. It is important to note that the k_{til} values derived from this technique represent average tillage erosion intensities over the last 35–45 years (depending on the sampling date) and are therefore lower than present-day k_{til} values, based on tillage erosion experiments, due to the increase of mechanical power during the last decades.

Although the erosivity of individual tillage operations used in non-mechanized agriculture is substantially lower than those used in mechanized agriculture (Table 6), crop rotation tillage transport coefficients reported are relatively high. Dercon *et al.* (unpublished data) obtained k_{til} values between 168 and 681 kg m^{-1} year^{-1} for a typical cropping cycle in the Andes. Nyssen *et al.* (2000) report an annual k_{til} value between 68 and 272 kg m^{-1} year^{-1} for agriculture in the Ethiopian highlands while Thapa *et al.* (1999a; 1999b) obtained k_{til} values between 260 and 710 kg m^{-1} year^{-1} for various tillage systems in intensive cropping systems in the humid tropics.

IV Rates of tillage erosion

While tillage transport coefficients allow comparison of potential tillage erosion intensity between tillage implements and management options, actual rates of tillage erosion are dependent on the interaction of tillage translocation with topography. In Table 7, we present tillage erosion rates reported in literature, based on direct measurement, ^{137}Cs data or derived from modelling studies. Erosion rates reported range between 3 and 70 Mg ha^{-1}yr^{-1} for mechanized agriculture. Despite the fact that tillage erosivity is generally higher for mechanized agriculture, erosion rates reported for non-mechanized agriculture are also high and range between 3 and 600 Mgha^{-1}yr^{-1}. The high values for non-mechanized agriculture must be attributed to the fact that most studies report rates on steep slopes in intensive cropping systems.

The significance of the tillage erosion process in the total soil redistribution on arable land can be derived from Table 7. Here, we report the relative contribution of tillage in the total soil redistribution on arable land for Europe, North and South America, Africa, Asia and Oceania. Two features are noteworthy. First, the data clearly indicates that, under mechanized agriculture, tillage erosion rates are at least in the same order of magnitude or higher than water erosion rates, in almost all cases. Second, tillage erosion also contributes substantially to the total soil redistribution under non-mechanized agriculture. These estimates of the relative importance of tillage and water erosion are consistent with the Canadian Agri-Environmental Indicator Project (McRae *et al.*, 2000), which is at present the only attempt to assess the significance of tillage erosion at the regional scale. It was concluded that approximately 50 % of the cropland in Canada was subject to unsustainable levels of tillage erosion (>6Mg ha^{-1}yr^{-1}) while only approximately 15% of the cropland was subject to unsustainable levels of water erosion. Equivalent data are not available for other regions. Direct estimation of tillage erosion rates for large areas is not always possible as detailed information about topographic curvature would be required, which cannot be reliably deduced from the large-scale DEMs which are presently available. In contrast to slope gradient (first terrain derivative), slope curvature (second terrain derivative) cannot be represented realistically, and is significantly underestimated, when derived from a coarse DEM (ie, +20 m resolution).

V Consequences for soil quality

Close relationships between the spatial distribution of tillage erosion and the spatial patterns of total C, N, P, texture, soil depth, rock fragment cover and above ground biomass have been reported (Van Oost *et al.*, 2000 b; Kosmas *et al.*, 2001; Quine and Zhang, 2002; Li *et al.*, 2004; Heckrath *et al.*, 2005). These results have provided evidence that tillage erosion operates like a conveyor belt, transferring soil and associated constituents from convexities to concavities. During cultivation,

Table 7 Comparison of tillage and water erosion rates, available in or calculated from the literature

Authors	Country	Tillage rate (Mg ha^{-1}yr^{-1})	Water rate (Mg ha^{-1}yr^{-1})	Ratio[a]
Mechanized agriculture				
St Gerontidis *et al.*, 2001	Greece	23	1	23
Tsara *et al.*, 2001	Greece	4.0–18		>15
Van Oost *et al.*, 2003a	Belgium	10	2	5
Lobb *et al.*, 1995	Canada	54		2.3
Poesen *et al.*, 1997	Spain	40–60		10
Kosmas *et al.*, 2001	Greece			>>1
Quine *et al.*, 2003	New Zealand	19		>>1
Quine and Zhang, 2002	UK			>>1
Quine *et al.*, 1997	Belgium			>1
Govers *et al.*, 1996	UK			>1
Montgomery *et al.*, 1997	USA			>1
Govers *et al.*, 1994	Belgium			1
Van Oost *et al.*, 2000a	Belgium	8.7	9.2	0.9
Schuller *et al.*, 2003	Chile			0.5–1.2
Dabney *et al.*, 1999	USA	81		0.3–1.5
Lobb and Kachanoski, 1999	Canada			0.2–1
Basher and Ross, 2002	New Zealand			0.15
Non-mechanized agriculture				
Thapa *et al.*, 1999a	Philippines	106–601		2.7
Quine *et al.*, 1999b	Lesotho	19	14	1.4
Quine *et al.*, 1999b	Zimbabwe	2.9	2.5	1.2
Thapa *et al.*, 2001	Philippines			>>1
Rymshaw *et al.*, 1997	Venezuela			>>1
Dercon *et al.*, 2003	Ecuador			>1
Nyssen *et al.*, 2001	Ethiopia			1
Nyssen *et al.*, 2000	Ethiopia			1
Lewis and Nyamulinda, 1996	Rwanda	68		1
Li and Lindstrom, 2001	China	16.9	17.9	0.9
Quine *et al.*, 1999c	China	14–55	10–29	0.5–5.5
Quine *et al.*, 1999b	China	18	34	0.5
Turkelboom *et al.*, 1997	Thailand	8–18	25–70	0.3
Li and Lindstrom, 2001	China	8.8	47.5	0.2
Quine *et al.*, 1997	China			<1
Zhang *et al.*, 1998	China			<<1

[a] Tillage erosion/water erosion rate ratio

there is a net loss of plough soil from convex slope elements. However, the plough layer depth is maintained here by incorporation of nutrient-poor subsoil into the plough layer. Consequently, the plough soil on these eroded convexities becomes depleted in surface-applied or surface-immobilized nutrients and the products of weathering. This depleted plough soil is also translocated away from the convexities and, therefore, areas of no (or limited) net soil loss on linear slope elements below convexities may also be characterized by nutrient-depletion of the plough soil. Conversely, plough soil accumulates in concavities through downslope translocation from the upslope landscape elements. These areas, therefore, develop overdeepened plough soil enriched in nutrients. Therefore, translocation of soil by tillage erosion is a major contributor to within-field variability in soil properties. Model simulations indicate that continuing tillage will further increase the spatial variability of soil properties (Quine and Zhang, 2002; Van Oost *et al.*, 2003b; de Alba *et al.*, 2004). Other studies provide evidence that tillage erosion has a deleterious impact on crop production (Aase and Pikul, 1995; Schumacher *et al.*, 1999; Kosmas *et al.*, 2001; Tsara *et al.*, 2001). More recently, Bakker *et al.* (2005) report on the effect of erosion-induced reductions in crop productivity on land-use change and concluded that the spatial pattern on land use is significantly affected by crop yield-erosion relationships. Tillage induced spatial variation in soil properties and crop yields is, however, not limited to mechanized agriculture. The importance of tillage in redistributing soil and soil constituents has also been recognized for non-mechanized agriculture, especially on terraced fields (Li and Lindstrom, 2001; Thapa *et al.*, 2001; Dercon *et al.*, 2003).

VI Discussion and conclusion

Although the tillage erosion experiments reported in literature were conducted in a variety of agricultural environments in terms of soil type, surface conditions and implement characteristics, the k_{til} values for different tillage implements are very consistent: the data available strongly suggests that tillage depth is the most important factor affecting tillage erosivity. Tillage erosivity increases exponentially with tillage depth. Reducing tillage depth can therefore be considered as an effective soil conservation strategy. Tillage direction also has an important control on tillage erosivity: tillage along the contour lines is substantially less erosive than tillage conducted up and down the slope.

Until now, very little attention has been paid to the role of implement shape on tillage erosivity. Although tillage erosivity could be well described as a function of tillage speed, depth, direction and soil bulk density, the results of some experiments indicate that this may have an influence. For example, the k_{til} values reported by (Quine and Zhang, 2004a) and (Heckrath *et al.*, 2006) for mouldboard tillage is much lower than other values reported using similar implements with identical operational characteristics and soil conditions. It is possible that implement shape may have caused lower tillage erosivity in these specific cases.

k_{til} values that are representative for whole crop cycle can be estimated by summing the individual k_{til} values for the different implements used. For mechanized agriculture, values reported are in the order of 470–780 kg m^{-1} year^{-1}. The lower end of crop rotation tillage transport coefficients estimates for non-mechanized agriculture are generally lower, ie, 68–260 kg m^{-1} year^{-1}. However, k_{til} values, reported for intensive cropping systems with a high frequency of tillage operations are in the same order of magnitude as those associated with mechanized agriculture.

Tillage erosion rates reported in literature indicate that this process significantly contributes to the removal and redistribution of topsoil on rolling arable land. Direct comparison of tillage erosion with water erosion rates for a data set covering the whole world indicates that tillage erosion rates are at least in the same order of magnitude or higher than water erosion rates, in almost all cases. It is worthwhile to compare the assessment of tillage erosion with estimates of water erosion intensity. Most available statistics on the extent and severity of soil erosion on arable land are unreliable (Boardman, 1998). This large uncertainty must be attributed to the high spatial and temporal variability of the processes involved (climate, soil erodibility, connectivity between upland landscape elements and streams, landscape erodibility role of extreme events, etc), which hampers accurate measurements. In contast, tillage erosion estimates are only dependent on topographical complexity (ie, slope curvature) and tillage management (ie, tillage transport coefficient) and are therefore quite robust. In the previous paragraphs, we have shown that tillage erosivity assessments are very consistent and allow to estimate k_{til} values with a relatively high precision.

Tillage erosion also has marked effects on soil quality: tillage will increase the spatial variation in soil properties and lead to a nutrient-depleted soil on convexities while a deep soil, enriched in nutrients, develops on concavities. This has important implications for dynamic processes such as soil organic carbon (SOC) and nitrogen turnover and storage in soils. With the progressive accumulation of nutrient-rich soil in low-lying areas of fields exposed to concentrated overland flow and leaching the risk of nutrient loss is prone to increase. Soil redistribution by tillage also results in a substantial modification of the landscape topography, which has direct consequences for surface and subsurface hydrology (eg, variability of infiltration, overland flow paths...). Studies have also reported on the close linkages between tillage erosion and crop productivity. The data available in literature strongly suggests that he impact of tillage erosion on soil quality and productivity will vary with the agro-environment. Shallower soils on hummocky terrain in drier climates, where soil depth is an important factor, suffer more adverse effects than soils in moderate climates.

Considering the widespread use of tillage practices and the high redistribution rates associated with the process, it is clear that tillage erosion should be considered in soil landscape studies and when developing environmentally sustainable farming practices. Although we now have a basic understanding of the most important controls, the consequences of tillage erosion for soil profile evolution and soil nutrients dynamics requires more attention. The integration of models of soil redistribution and soil property evolution with models of soil nutrient cycling therefore represents a major challenge.

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