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Review Article

TILLAGE EROSION: THE PRINCIPLES, CONTROLLING FACTORS AND MAIN IMPLICATIONS FOR FUTURE RESEARCH

Agnieszka Wysocka-Czubaszek[1], **Robert Czubaszek**[1]

[1] Department of Environmental Protection and Management, Białystok University of Technology, Wiejska 45A, 15-351 Białystok, Poland, e-mail: a.wysocka@pb.edu.pl; r.czubaszek@pb.edu.pl

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ABSTRACT

Tillage erosion is one of the major contributors to landscape evolution in hummocky agricultural landscapes. This paper summarizes the available data describing tillage erosion caused by hand-held or other simple tillage implements as well as tools used in typical conventional agriculture in Europe and North America. Variations in equipment, tillage speed, depth and direction result in a wide range of soil translocation rates observed all over the world. The variety of tracers both physical and chemical gives a challenge to introduce the reliable model predicting tillage erosion, considering the number and type of tillage operation in the whole tillage sequence.

Keywords: tillage erosion, erosion rates, soil redistribution.

INTRODUCTION

While water and wind erosion are still considered to be the dominant processes degrading soil on agricultural land, there is a growing recognition that another type of erosion is a serious contributor to changes in soils and landscapes. The tillage erosion had got the special attention from researchers in the last two decades. The first attempt of measuring the tillage erosion was made in 1940s, in Poland the investigations on tillage erosion started in the 1950's. The results revealed that soil translocation depends on the ploughing direction and slope gradient. In subsequent years only a few authors conducted studies on tillage erosion. However, this phenomenon did not receive much attention until the 1990's, when more and more papers considered studies on this type of erosion. In Poland tillage erosion rates were measured mainly on loess soils. The relationship between tillage erosion and landscape features as well as the effect of tillage erosion on the soil profiles variability along the slope were investigated [Zgłobicki 2002]. Although large amount of studies have been conducted still some uncertainties exist. This paper describes the principles and effects of tillage erosion; factors controlling soil movement; rates of soil translocation and erosion as a result of using various tillage tools; methods of research; and draw conclusions for further investigations.

DEFINITION, MAIN PRINCIPLES AND EFFECTS

Tillage erosion is, by the definition, the displacement of cultivated layer during tillage. The soil uplift by the tillage tools is always perpendicular to the sloping surface of the land while the soil falls back perpendicular to the horizontal plane due to gravity. The translocation of soil is expressed as its moved mass in a specific direction per meter width. The soil is transported downslope during the tillage operation conducted in the downward direction, while during upward tillage the upslope soil translocation occurred. However due to gravitational forces smaller mass of soil is moved in the upward direction during the upslope cultivation. That is why the net soil distribution on the field is in downslope direction. Topography, especially the slope angle, is the most important control on the redistribution of soil particles by tillage. The steeper the slope gradient the larger is the difference between the vectors of upward and downward movement creating a net movement downslope and that is why tillage erosion depends mainly on tillage direction and slope gradient [Govers et al. 1999]. During te ploughing three phases of motion can be distinguished: (i) drag, when the soil is in contact with tillage tool; (ii) jump, when the soil loses this contact and (iii) rolling, when the clods and particles roll and jump with close contact to soil surface [Torri et al. 2002]. The amount of tillage erosion increases with the number of tillage operations [De Alba et al. 2004], the tillage depth [Van Muysen et al. 2002], and tillage speed [Van Muysen et al. 2000, 2002]. In experimental study with donkey-drawn mouldboard ploughing, in the top slope position, the soil surface level decreased by 0.57 m after 10 operations and by 0.23 after next 10 operations. Further decrease of 0.17 m was observed after next 10 operations [Li et al. 2004]. The increasing tillage depth in mouldboard ploughing by 0.4 m, despite reducing the speed from 1.81 to 1.54 and 1.45 m s^{-1} increased the soil translocation rate from 155 kg m^{-1} per operation to 223 and 281 kg m^{-1} per operation, respectively. The decreasing of the tillage speed by 0.27 m s^{-1} results in reduction of soil translocation rate by 68 kg m^{-1} per operation [Van Muysen et al. 2002]. The initial soil conditions also play an important role in tillage erosion [Van Muysen et al. 2000]. The experiment with mouldboard ploughing on different soil conditions: (i) pre-tilled soil and (ii) grass fallow, resulted in higher soil displacement distance in the tillage conducted on pre-tilled soil than on the compact soil in grass fallow. Greater ploughing depth and mechanical behavior of the pre-tilled soil affected the particle movement. Dense grass roots and high degree of consistency in grass fallow soil resulted in strong soil clods, which were more difficult to move [Van Muysen et al. 1999].

Tillage erosion leads to surface denudation on convex parts of hillslope and soil accumulation on the concave areas [De Alba et al. 2004], which is in opposite with water erosion pattern. Soil erosion modeled by WATEM on the basis of the digital elevation model on the field cultivated for at least 100 years revealed that soil loss caused by water erosion occurred on almost whole slope, with lowest rates near the summit and highest on the backslope position. The accumulation of soil moved with water erosion was on the toeslope and in the depression, where was the highest. The tillage erosion transported soil mainly from shoulder slope, and accumulation occured on the footslope and toeslope. Opposite to the water erosion the lowest soil loss by tillage erosion was predicted on the lower backslope, because the amount of soil translocated to this part of slope was equal to the amount of soil removed from this slope position. However in complex landscape the soil loss rates on the convexities and accumulation rates in concavities decrease with time [Li et al. 2008].

De Alba et al. [2004] has proposed new theoretical two-dimensional model of soil catena evolution due to soil redistribution by tillage. Soil profile truncation occurs on convexities and in the upper areas of the cultivated hillslopes; while the opposite effect takes place in concavities and the lower areas of the field where the original soil profile becomes buried and deep colluvial soils develop [Heckrath et al. 2005]. At sectors of rectilinear morphology in the hillslope (backslope positions), a null balance of soil translocation takes place, independent of the slope gradient and of the rate of downslope soil translocation. As a result, in those backslope areas, a substitution of soil material in the surface horizon with material coming from upslope areas takes place. This substituted material can produce an inversion of soil horizons in the original soil profile and sometimes the formation of ‘‘false truncated soil’’ [De Alba et al. 2004].

Govers et al. [1996] stated that soil translocation is important geomorphological process and tillage erosion rates may exceed 10 Mg ha^{-1} yr^{-1}, which is equal to water erosion reported in Europe on hilly landscape. This can be confirmed by comparison of the annual sheet and rill erosion rate against tillage erosion in Europe. The actual mean sheet and rill erosion rates in Europe are in the range of 0.1–8.8 Mg ha^{-1} yr^{-1} and mean tillage erosion is between 3.0 and 9.0 Mg ha^{-1} yr^{-1} [Verheijen et al. 2009]. Tillage erosion was found to be a main process redistributing the soil particles in conventionally tilled corn-based production [Lobb et al. 1999] and cereal-based production [Kosmas et al. 2001]. Van Oost et al. [2005] have compared rates of soil erosion by tillage with those by water. By comparing two time periods, they found that there has been a shift from water-dominated to tillage-dominated erosion processes in agricultural areas during the past few decades. This reflects the increase in mechanized agriculture and the authors concluded that where soil is cultivated, tillage erosion may lead to larger losses than overland flow. However, the contributions of water and tillage erosion towards total soil erosion vary across topographically complex landscapes and their patterns are mainly dependent on topographic features. On undulating areas, tillage and water erosion both contribute in similar rate to total soil erosion while on hummocky landscapes, tillage erosion dominates, and the effects of water erosion are minor [Li et al. 2008]. Li and Lindstrom [2001] concluded that water erosion is the main factor responsible for decline in soil quality on the steep slopes in Chinese Loess Plateau, but tillage erosion is an equal contributor in soil quality deterioration on the terraced hill slopes.

Field borders, fences, and vegetated strips that interrupt soil fluxes also contribute to the erosion pattern by leading to the creation of topographic discontinuities or lynchets. The translocation of soil by tillage and water erosion on the terraced hill slope creates lynchets and enriches soils in the lower end of terrace in nitrogen and organic matter [Li, Lindstrom 2001]. The repeated translocation of soil in one direction with tillage tools that preferentially move soil to one side, create berms and a ‘‘dead furrow’’ or channel on opposite sides of the tilled domain [Vieira, Dabney 2011]. Thapa et al. [1999b] attempted to evaluate four tillage systems (i) contour mouldboard ploughing in the open field; (ii) contour soil barriers formed by ridge tillage in the open field; (iii) contour barriers formed by natural grass strips plus mouldboard ploughing; and (iv) contour barriers formed by a combination of ridge tillage and natural grass strips. The results show that both ridge tillage and natural grass barrier strips reduce tillage erosion rates for corn production on steepland soils in the humid tropics. In case of olive fields frequently ploughed by a local, donkey-drawn tillage implement the maximum soil loss values for contour tillage, were almost nine times less than for up and down tillage [Barneveld et al. 2009]. However, the case studies from Yanting, in Sichuan Province, China; Ha Sofonia, in Lesotho; and, Chinamora, in Zimbabwe confirm the importance of tillage erosion and translocation on terraces and contour-strips subjected to cultivation by animal traction. Rates of tillage erosion were comparable or greater than water erosion on the examined fields [Quine et al. 1999a]. On the other hand, land consolidation, typical for European agriculture contributes to acceleration of tillage erosion by the conversion of depositional areas into terrains which generates the soil loss [Chartin et al. 2013].

Tillage erosion has been described as the major cause of physical soil degradation in rolling agricultural landscapes. The long-term effects of soil redistribution by tillage increase the variability of soil properties [Kosmas et al. 2001], transform soil profile morphology and landscapes [De Alba et al. 2004], and lead to a significant decline in soil productivity. Tillage erosion led to truncated soil profiles on the shoulderslopes [De Alba et al. 2004] and developing of nutrient-rich and deep colluvial soil in the concave part of slope. Therefore, the within-field variability of soil properties in arable lands on the slope is controlled by tillage erosion which affected the redistribution of carbon and its field budget and nutrient losses [Heckrath et al. 2005]. Tillage erosion within the field borders is a key driver of net carbon cycle. According to studies based on CORINE, land use and the assumption that soils contain on average 2% of carbon, tillage erosion and deposition results in the burial of *c.* 7 Tg C y^{-1} [Van Oost et al. 2009]. Although the content of soil organic matter and available nutrients increase in the areas of soil accumulation [Li, Lindstrom 2001, Li et al. 2004] the long term enrichment of lowerings exposed to concentrated water flow may increase the amount of nutrient lost from the field [Heckrath et al. 2005, Van Oost et al. 2009] via water erosion as well as by leaching in more moist environment.

METHODS OF TILLAGE EROSION MEASUREMENT

Tillage translocation, defined as a transport and resultant displacement of soil by tillage [Govers et al. 1999], can be measured with a tracer method, i.e. a volume of soil is labeled and tilled, and then changes in tracer concentrations before and after tillage are used to calculate soil translocation. The tracer method for measuring soil translocation includes physical and chemical ones. Physical tracers are: metal cubes [Van Muysen et al. 1999], flat steel washers [Montgomery et al. 1999], magnetic tracers [Zhang et al. 2009], rock fragments [Nyssen et al. 2000] and gravels [Zhang et al. 2004]. Chemical tracers are radionuclides [Zgłobicki 2002] and chlorides [Lobb et al. 1999].

One of the most common physical tracers are the numbered aluminum cubes, which are placed in a series of holes and their positions are precisely recorded using a theodolite. After the treatment the areas immediately up- and downslope of the origin location are excavated and the position of each tracer is recorded. The use of metal detector to locate the tracers that moves relatively large distance allows a tracer recovery rate higher than 98% [Van Muysen et al. 2002]. Another popular tracers are brightly coloured gravels, or dyed aquarium gravel or stone chips [Turkelboom et al. 1999, Nyssen et al. 2000, Li et al. 2004, Zhang et al. 2004, Tiessen et al. 2007b]. The magnetic tracer is used seldom and it can be derived from the residues of brick and tile kilns, consisting of calcined soil and coal. The plots perpendicular to the tillage direction are established on the study fields. The soil from each plot is excavated and mixed with tracer and then returned to the plot. The magnetic strength of labeled soil in plot and soil prior to the application of the magnetic tracer must be measured to determine background and can be detected with a magnetometer, which commonly is used for the magnetic measurements of soil, rock, mine, brick, tile, cement, semiconductor, etc. The magnetic tracer was introduced to measure the soil translocation in conventional and conservation hoe-tilling in China [Zhang et al. 2009].

There are two methods of calculating translocation using plots filled with physical tracers. The Distribution-Curve Method, which is more common method, allows the calculation of soil translocation directly from the distributions of tracer after tillage. Summation-Curve Method, which is a less frequently used method, calculates the translocation from a summation curve generated from the distribution of tracer after tillage by employing convolution. Lobb et al. [2001] described and compared both methods using hypothetical and experimental data. Both methods provide accurate measures of gross translocation, but the Summation-Curve Method provides a measure of error associated with gross translocation and a more thorough characterization of the dispersion of translocated soil.

Besides using the aggreagate-sized physical tracer tillage erosion can be measured by marking the soil matrix with chemical tracers such as chlorides. The chloride (KCl - greenhouse grade muriate of potash) [Lobb et al. 1999] or sodium chloride solution can be used to measure the tillage erosion. The comparison of aluminium cubes and sodium chloride tracers revealed that there were no significant differences between these two methods [Barneveld et al. 2009].

However, one of the most popular tracers is ^{137}Cs used by many authors who confirmed its reliability and accuracy in measuring of the soil translocation and redistribution on the slope as a result of water and tillage erosion [eg. Pennock 2003, Zgłobicki 2002]. The ^{137}Cs technique provides data which are spatially distributed, shows the net effect of all types of erosion and provides the medium-term average erosion rates, on the basis of just single site visit. It is a manmade radionuclide, which was generated during the atmospheric testing of thermonuclear-weapons conducted in the 1950s and early 1960s and deposited onto the Earth's surface through wet and dry precipitation. After deposition to the Earth's surface, ^{137}Cs is quickly and strongly adsorbed by soil particles which makes it nonexchangeable. Therefore, its redistribution across the landscape is related to the redistribution of soil particles and that is why ^{137}Cs is used as a tracer indicating the physical movement of soil by erosion processes. The ^{137}Cs inventories (total activity in the soil profile per unit area) measured at the study site is compared with an estimate of the total atmospheric input, which is represented by the mean ^{137}Cs inventory obtained at a "reference site". Areas which evidence ^{137}Cs loss are identified as suffering net erosion and net ^{137}Cs gain indicates the deposition.

In order to derive quantitative estimates of erosion rates the calibration is needed which can be done by a mass-balance model or by means of proportional model which uses a simple linear function to convert the loss or gain of ^{137}Cs inventory (compared to a reference level) to a loss or gain of soil mass, respectively [Walling et al. 2002]. The research of Li et al. [2010] on proportional model and three types of mass-balance models proposed by Walling et al. [2002] revealed that all four conversion models are highly sensitive to the input values of the reference ^{137}Cs level, particle size correction factors and tillage depth. Another approach is represented by a model of Van Oost et al. [2003], which integrates a ^{137}Cs mass-balance model with spatially distributed soil erosion models where all processes significantly contributing to the redistribution of soil are independently simulated in a two dimensional spatial context.

One must bear in mind that the ^{137}Cs technique determines the impact of water and tillage erosion, so there still remains the problem of separating the contributions of water erosion and tillage to the pattern of net ^{137}Cs redistribution. The contribution of the individual processes can be identified by comparison of ^{137}Cs-derived soil redistribution rates with the water erosion model predictions. Although the ^{137}Cs inventory is mainly used to evaluate the tillage soil redistribution within single landscape unit the research of Pennock [2003] revealed that ^{137}Cs may be used at regional scale. However, the Chernobyl accident occurred on the 26th of April 1986 resulted in significant fallout of among others ^{137}Cs in Poland and other northern and eastern countries in Europe. In Poland Zgłobicki [2002] used ^{137}Cs tracer as one of the method to investigate the denudation in north-western part of the Lublin Upland and overcame the problem by indirect quantification of the ^{137}Cs from Chernobyl fallout.

Recently, the measurements using lead-210 (^{210}Pb$_{ex}$) has become recognized as an effective tool for documenting the soil translocation in many landscapes. Gaspar et al. [2013] used this tracer to measure soil redistribution caused by erosion and cultivation in mountain Mediterranean landscapes. Also plutonium isotopes (^{239}Pu and ^{240}Pu) originated from atmospheric nuclear weapons tests were used for soil redistribution investigations in a catchment in Australia. The Pu measured with accelerator mass spectrometry (AMS) method allows to use 4-20 g samples and to measure much more samples than ^{137}Cs measured by γ-ray spectroscopy, what allows to perform more detailed investigations [Hoo et al. 2011].

Olson et al. [2002] used the fly ash, the product of high temperature coal combustion, together with magnetic minerals, magnetic susceptibility, and organic C content of a soil to estimate the extent of soil loss as a result of human activities at the cultivated field in Pushkino, Russia. Deposition of fly ash derived from distant railway traffic started around 1851 and increased in 1870 as a result of closer construction of a railway. Tillage and accelerated erosion redistributed the fly ash causing the deposition of sediment rich in fly ash on the lower and upper footslopes of the field. The estimated annual soil loss amounts to an average of 4.7 Mg ha^{-1} yr^{-1} for the past 60 to 80 years based on loss of fly ash and reduction in magnetic susceptibility [Olson et al. 2002]. Recently Olsen et al. [2013] combined the fly ash technique with ^{137}Cs to determine soil erosion rates for past cropland from 1910 till nowadays. Measuring of soil magnetic susceptibility is another fast and non-destructive method for estimation the amount of soil redistributed by tillage erosion within the landscape [Jordanova et al. 2011].

Several models were proposed to calculate the tillage erosion. Lindstrom et al. [1990] developed the first model of soil translocation by tillage as a statistical relationship between soil displacement and slope gradient. Govers et al. [1999] introduced the transport coefficient *k* (kg m^{-1} per tillage operation) to relate the net unit soil transport rate due to a specific tillage operation to the slope gradient. The Tillage Erosion Prediction (TEP) model developed by Lindstrom et al. [2000], can predict soil redistribution along single slope profiles. Van Oost and Govers [2000] developed the Water and Tillage Erosion Model (WATEM), which simulates 2D patterns of soil redistribution using a diffusion-type equation and assumes that all soil translocation occurs in the direction of steepest slope, irrespective of the pattern of tillage. The SORET model is of the spatial distribution type and can perform 3D simulations of soil redistribution in Digital Terrain Models (DTMs) on the field scale. It can predict soil redistribution arising from different patterns of tillage in a given landscape via computer simulation of a single tillage operation, and is also able to forecast the long-term effects of repeated operations [De Alba 2003]. A tillage translocation model (TillTM) is a two-dimensional model (in the horizontal and vertical dimensions), where there are the topography data and soil constituent concentrations as a function of depth at a series of data points along the tillage direction [Li et al. 2008]. A diffusion-type model Directional Tillage Erosion Model (DirTillEM) was developed to better account for the effect of complex tillage patterns and field boundaries on tillage erosion across an agricultural landscape [Li et al. 2009]. Recently Vieira and Dabney [2011] developed a two-dimensional Tillage Erosion and Landscape Evolution model which allows complex internal boundaries to be defined within the simulation domain i.e. the model allows prediction of the formation of edge-of-field berms by defining alternative boundary conditions.

ERODIBILITY OF TILLAGE OPERATIONS

The tillage erosion was measured for many different tillage operations. In Thailand, Turkelboom et al. [1999] measured the tillage erosion by manual hoeing on steep slopes (32–82%). The experimental data showed that one tillage pass results in soil flux in the range from 390 to 870 kg m^{-1}, depending on the slope angle. The soil loss from the typical field located on the slope of 30–50% was estimated at 8–18 Mg ha^{-1}. Two typical hoe-tilling methods: (i) hoe-tilling in its conventional approach and (ii) protective non-overturning hoeing tillage, were applied on several terraces with different slope angles. The investigations revealed that translocation rates ranged from 46.47 to 113.62 kg m^{-1} per tillage pass, depending on the slop angle. The conservation approach of hoe tillage causes the decrease of soil downslope translocation to a range from 19.45 to 39.62 kg m^{-1} per tillage pass and results in a significant reduction in tillage erosion [Zhang et al. 2009].

Oxen-pulled ard tillage is another simple and popular method of tillage still used in Africa and Asia. The experiment was carried out in Ethiopia, on the terraced slope, where the tillage was parallel to the contour. The soil flux ranged from 4.8 to 38.7 kg m^{-1} and tillage erosion rates were smaller than those observed for mechanized tillage [Nyssen et al. 2000]. The experiment conducted in China with donkey-drawn mouldboard plough along the contours revealed high net accumulation of soil in the lower slope position after 50 operations. According to direct measurement using differential global positioning system the soil surface level at the top of the slope decreased by 1.25 m and increased by 1.33 m at the slope bottom [Li et al. 2004]

Although several authors paid attention to the hand-held or other simple tillage implements, majority of papers contributing to issue of erodibility of tools reported the translocation rates of implements used in typical conventional agriculture in Europe and North America. The displacement distance during mouldboard plough on silt loams were from 0.23 m downslope on the linear-convex backslope to 0.50 m during downslope operation on the convex shoulder [Montgomery et al. 1999]. On the shale-sandstone soils, on 21% slope the translocation of soil during mouldboard ploughing in the downward direction was 0.42 m and 0.16 m during upward tillage pass [Kosmas et al. 2001]. In up and downward mouldboard tillage the soil translocation in the direction of tillage depends on slope gradient [Van Oost et al. 2000], tillage depth and speed, while in case of contour tillage soil movement is affected by slope gradient together with tillage speed. On the basis of these conclusions, the model was developed which allows to evaluate the effect of tillage depth, speed and/or tillage direction on the soil erosivity of a mouldboard ploughing [Van Muysen et al. 2002]. The mouldboard causes the asymmetric soil movement so the final rate of soil translocation should be determined on the basis of complex interaction between the morphology of the relief and the direction of tillage. The horizontal cutting angle of the mouldboard blades in relation to the forward direction of the tractor plays main role in soil movement intensity in complex landscapes. The direction different than perpendicular to the slope might be the controlling factor in reducing tillage erosion of mouldboard plough. The results of experiment based on tillage performed on sandy loam soils in 3 directions: (i) up- and downwards the slope, (ii) slantwise down and slantwise up, and (iii) contour, revealed that tillage in up and down at 45^{o} to the maximum slope with turning soil upslope was the least erosive. Simulation of tillage erosion in complex topography by mouldboard plough revealed that contour tillage leads to higher average erosion rate what questions the role of this type of tillage in reducing the tillage erosion [De Alba 2003]. Also in potato cropping system the conservation tillage did not reduce the tillage erosion [Tiessen et al. 2007b].

The erosivity of primary tillage operations including mouldboard plough and chisel plough and the erosivity of secondary tillage with offset disc and vibrashank on the field with potato crop in undulating landscape of Canada on loamy soils were also measured. The results showed that both primary and secondary implements were very erosive, the average soil displacement measured for each operation was around 3 m, with maximum equal to 5.6 m for chisel plough and vibrashenk. The mass translocation was the highest for chisel plough, following the mouldboard plough, vibrashenk and offset disc [Tiessen et al. 2007b]. However Lobb et al. [1999] findings were contrary, because in their experiment the highest mass translocation was measured for moudlboard plough (72 kg m^{-1}), following chisel plough (62 kg m^{-1}) and tandem disc (56 kg m^{-1}), and field cultivator (41 kg m^{-1}). In case of chisel plough, tandem disc and field cultivator tillage translocation was slope gradient dependent. The tillage depth and speed affected the rate of erosion as well, but in complex landscape these two parameters are highly variable due to changing topographic and soil conditions [Lobb et al. 1999].

In potato production the tertiary tillage operations such as planting, hilling and harvesting result in significant soil translocation and can be equally as erosive as primary and secondary tillage operations. The harvester and sequence of planting, hilling and harvesting displace the soil up to 6.0 m and 23.6 m respectively, which is much greater distance than those resulted from primary and secondary operations [Tiessen et al. 2007a]. The tandem disc and field cultivator were also found as the erosive implements [Lobb et al. 1999]. Chisel tillage is another very erosive operation. In Belgian Loam Belt chisel tillage caused denudation rate more than 1 mm per tillage operation. This type of operation is usually combined with mouldboard ploughing, also one of the most erosive operations resulting in total annual tillage erosion rate equal to 3 mm per year [Van Muysen et al. 2000]. Chisel tillage was the most erosive operation in potato cultivation with mass movement per one operation equal to 64.4 kg m^{-1} [Tiessen et al. 2007b]. This type of tillage operation translocate the fine earths over larger distance than coarse material.

Although the recognition of erosivity of one operation is very important, under the normal conditions, farmers use several operations, required various equipment, during the year for crop cultivation. Transport coefficient for the whole tillage experiment using an implement sequence of a rotary harrow and seeder was 123 kg m^{-1} per tillage operation and suggests that these operations contribute significantly to soil displacement and tillage erosion [Van Muysen, Govers 2002]. The soil movement resulted from a typical tillage sequence, including multiple mouldboard, chisel and harrow passes was studied by Van Muysen et al. [2006] on Luvisols, Cambisols and Regosols, which have developed in loess deposits in Belgian Loess Belt. The soil displacement rate for tillage sequence was 2342 kg m^{-1} per tillage sequence and 167 kg m^{-1} per tillage operation. The results also revealed that total erosivity of different tillage operation cannot be calculated by summing up the erosivity of single operations, because total erosivity of tillage sequence is highly dependent on the tillage direction of every pass [Van Muysen et al. 2006], which can be difficult or even impossible to obtain. The study on four tillage implements: air-seeder, spring-tooth-harrow, light-cultivator and deep-tiller used as a typical conventional tillage sequence for cereal-based production in Canadian Prairies revealed that erosivity of air-seeder and spring-tooth-harrow were much lower than that of light-cultivator and deep-tiller, but their effect on total erosion has to be taken into account especially when those implements are used just after other tillage operations. However, the erosivity of full sequence in this tillage system was considerably lower than those with a mouldboard plough [Li et al. 2007].

THE RATES OF TILLAGE EROSION

The rates of tillage erosion have been reported all over the world. In Denmark average tillage erosion on glacial till on the typical hillslope of terminal moraine amounts to 27 Mg ha^{-1} yr^{-1} on the shoulderslopes, while deposition of 12 Mg ha^{-1} yr^{-1} was measured on foot- and toeslopes [Heckrath et al. 2005]. In Canada on glacial till in the hummocky landscape, convex slopeshoulders had the highest mean soil loss rates of 33 Mg ha^{-1} yr^{-1}, with the mean deposition rate on concave footslope was equal to 10 Mg ha^{-1} yr^{-1} [Pennock 2003]. The estimated soil erosion rates for pasture was 21 Mg ha^{-1} yr^{-1} and 38 Mg ha^{-1} yr^{-1} for crop rotation with potatoes in area of Prince Edward Island, Canada. The highest losses occurring on the slope shoulder suggest that tillage erosion is the major contributor in overall erosion [Kachanoski, Carter 1999]. In humid climate the mean annual soil loss from the contour mouldboard ploughing in the open field amounted to 63 Mg ha^{-1} yr^{-1}, while the soil loss was reduced by 30% during contour mouldboard ploughing within contour natural grass barrier strips, the reduction for contour ridge tillage in the open field was 45% and for contour and for natural grass barrier strips plus ridge tillage was 53% [Thapa et al. 1999b]. Conservation hoeing tillage reduced the tillage erosion rates from 78 to 28 Mg ha^{-1} yr^{-1} in the hilly areas in China [Zhang et al. 2009]. In China the tillage erosion was estimated from 50 to 150 Mg ha^{-1} yr^{-1} [Zhang et al. 2004]. The estimated mean tillage erosion rates on ribbon terraces was equal to 55 Mg ha^{-1} yr^{-1}, while on the shoulder terraces decreased to 14 Mg ha^{-1} yr^{-1} [Quine et al. 1999a].

CONCLUSIONS

Tillage erosion is major contributor in within-field variability of soil properties with important implications for nutrient losses and decline of crop productivity. The widespread use of tillage practices and high redistribution rates associated with process indicate that tillage erosion should be considered in soil landscape studies and when developing environmentally sustainable farming practices. The implications for further investigations are as follows:

1. According to the authors' knowledge there is no investigation comparing the rate of tillage erosion according to the age of equipment. In Poland many farmers have recently bought the latest equipment, so this may be an accelerating factor for tillage erosion.
2. The total erosivity of full sequence in various tillage systems was paid little attention except a few papers considering this issue. The proper methodology and interactions of various tillage operations in one crop rotation need further investigations.
3. The influence of tillage erosion on changes in old-glacial landscape, especially in Poland requires more research. Understanding of erosion processes on the gentle sandy slopes and their quantification may contribute to better principles in modern agriculture, which may control the nutrient accumulation in lowerings and valley bottoms.
4. The variety of tracers both physicals and chemicals gives a challenge to introduce a reliable model predicting not only tillage erosion but also water erosion, considering the number and type of tillage operation in the whole tillage sequence. The new tracers, especially isotopic radionuclides, need more investigations to provide reliable models for erosion rate calculation.

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REFERENCES

1. Barneveld R.J., Bruggeman A., Sterk G., Turkelboom F. 2009. Comparison of two methods for quantification of tillage erosion rates in olive orchards of north-west Syria. Soil Till. Res. 103, 105–112.
2. Chartin C., Evrard O., Salvador-Blanes S., Hinschberger F., Van Oost K., Lefèvre I., Daroussin J., Macaire J.-J. 2013. Quantifying and modelling the impact of land consolidation and field borders on soil redistribution in agricultural landscapes (1954–2009). Catena 110, 184–195.
3. De Alba S. 2003. Simulating long-term soil redistribution generated by different patterns of mouldboard ploughing in landscapes of complex topography. Soil Till. Res. 71, 7–86.
4. De Alba S., Lindstrom M., Schumacher T.E., Malo D.D. 2004. Soil landscape evolution due to soil redistribution by tillage: a new conceptual model of soil catena evolution in agricultural landscapes. Catena 58, 77–100.
5. Gaspar L., Navas A., Machin J., Walling D.E. 2013. Using $^{210}Pb_{ex}$ measurements to quantify soil redistribution along two complex toposequences in Mediterranean agroecosystems, northern Spain. Soil Till. Res. 130, 81–90.
6. Govers G., Lobb D.A., Quine T.A. 1999. Tillage erosion and translocation: emergence of a new paradigm in soil erosion research. Soil Till. Res. 51, 167–174.
7. Govers G., Quine T.A., Desmet P.J.J. Walling D.E. 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. Earth Surf. Process. Landforms 21, 929–946.
8. Heckrath G., Djurhuus J., Quine T.A., Van Oost K., Govers G., Zhang Y. 2005. Tillage Erosion and Its Effect on Soil Properties and Crop Yield in Denmark. J. Environ. Qual. 34, 312–324.
9. Hoo W.T., Fifield L.K., Tims S.G., Fujioka T., Mueller N. 2011. Using fallout plutonium as a probe for erosion assessment. J. Environ. Radioactivity 102, 937–942.
10. Jordanova D., Jordanova N., Atanasova A., Tsacheva T., Petrov P. 2011. Soil tillage erosion estimated by using magnetism of soils—a case study from Bulgaria. Environ Monit Assess. 183, 381–394.
11. Kachanoski R.G., Carter M.R. 1999. Landscape position and soil redistribution under three soil types and land use practices in Prince Edward Island. Soil Till. Res. 51, 211–217.
12. Kosmas C., Gerontidis St., Marathianou M., Detsis B., Zafiriou Th., Van Muysen W., Govers G., Quine T.A., Van Oost K. 2001. The effect of tillage displaced soil on soil properties and wheat biomass. J. Soil Till. Res. 58, 31–44.
13. Li S., Lobb D.A., Lindstrom M.J. 2007. Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. Soil Till. Res. 94, 164–182.

14. Li S., Lobb D.A., Lindstrom M.J., Farenhorst A. 2008. Patterns of water and tillage erosion on topographically complex landscapes in the North American Great Plains. J. Soil Water Conserv. 63 (1), 37–46.
15. Li S., Lobb D.A., Tiessen K.H.D. 2009. Modeling tillage-induced morphological features in cultivated landscapes. Soil & Tillage Research 103, 33–45.
16. Li S., Lobb D.A., Tiessen K.H.D., McConkey B.G. 2010. Selecting and Applying Cesium-137 Conversion Models to Estimate Soil Erosion Rates in Cultivated Fields. J. Environ. Qual. 39, 204–219.
17. Li Y., Lindstrom M.J. 2001. Evaluating Soil Quality–Soil Redistribution Relationship on Terraces and Steep Hillslope. Soil Sci. Soc. Am. J. 65, 1500–1508.
18. Li Y., Tian G., Lindstrom M.J., Bork H.R., 2004. Variation of Surface Soil Quality Parameters by Intensive Donkey-Drawn Tillage on Steep Slope. Soil Sci. Soc. Am. J. 68, 907–913.
19. Lindstrom M.J., Nelson W.W., Schumacher T.E., Lemme G.D. 1990. Soil movement by tillage as affected by slope. J. Soil Till. Res. 17, 255–264.
20. Lindstrom M.J., Schumacher J.A., Schumacher T.E., 2000. A Tillage Erosion Prediction model to calculate soil translocation rates from tillage. J. Soil Water Conserv. 55, 105–108.
21. Lobb D.A., Kachanoski R.G., Miller M.H. 1999. Tillage translocation and tillage erosion in the complex upland landscapes of southwestern Ontario, Canada. Soil Till. Res. 51, 189–209.
22. Lobb D.A., Quine T.A., Govers G., Heckrath G., 2001. Comparison of methods used to calculate tillage translocation using plot-tracers. J. Soil Water Conserv. 56, 321–328.
23. Montgomery J.A., McCool D.K., Busacca A.J., Frazier B.E. 1999. Quantifying tillage translocation and deposition rates due to moldboard plowing in the Palouse region of the Pacific Northwest, USA. Soil Till. Res. 51, 175–187.
24. Nyssen J., Poesen J., Haile M., Moeyersons J., Deckers J. 2000. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. Soil Till. Res. 57, 115–127.
25. Olson K. R., Gennadiyev A.N., Jones R.L., Chernyanskii S. 2002. Erosion Patterns on Cultivated and Reforested Hillslopes in Moscow Region, Russia. Soil Sci. Soc. Am. J. 66, 193–201.
26. Olson K.R, Gennadiyev A.N., Zhidkin A.P, Markelov M.V., Golosov V.N., Lang J.M. 2013. Use of magnetic tracer and radio-cesium methods to determine past cropland soil erosion amounts and rates. Catena 104, 103–110.
27. Pennock D.J. 2003. Terrain attributes, landform segmentation, and soil redistribution. Soil Till. Res. 69, 15–26.
28. Quine T.A., Walling D.E., Chakela Q.K., Mandiringana O.T., Zhang X. 1999a. Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from caesium-137 measurements. Catena 36, 115–142.
29. Thapa B.B., Cassel D.K., Garrity D.P. 1999b. Ridge tillage and contour natural grass barrier strips reduce tillage erosion. Soil Till. Res. 51, 341–356.
30. Tiessen K.H.D., Lobb D.A., Mehuys G.R., Rees H.W. 2007a. Tillage translocation and tillage erosivity by planting, hilling and harvesting operations common to potato production in Atlantic Canada. Soil Till. Res. 97, 123–139.
31. Tiessen K.H.D., Mehuys G.R., Lobb D.A., Rees H.W. 2007b. Tillage erosion within potato production systems in Atlantic Canada I. Measurement of tillage translocation by implements used in seedbed preparation. Soil Till. Res. 95, 308–319.
32. Torri D., Borselli L. 2002. Clod movement and tillage tool characteristics for modelling tillage erosion. J. Soil Water Conserv. 57, 24–28.
33. Turkelboom F., Poesen J., Ohler I., Van Keer K., Ongprasert S., Vlassak K. 1999. Reassessment of tillage erosion rates by manual tillage on steep slope in northern Thailand. Soil Till. Res. 51, 245–259.
34. Van Muysen W., Govers G. 2002. Soil displacement and tillage erosion during secondary tillage operations: the case of rotary harrow and seeding equipment. Soil Till. Res. 65, 185–191.
35. Van Muysen W., Govers G., Bergkamp G., Roxo M., Poesen J. 1999. Measurement and modelling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. Soil Till. Res. 51, 303–316.
36. Van Muysen W., Govers G., Van Oost K. 2002. Identification of important factors in the process of tillage erosion: the case of mouldboard tillage. Soil Till. Res. 65, 77–93.
37. Van Muysen W., Govers G., Van Oost K., Van Rompaey A. 2000. The effect of tillage depth, tillage speed and soil condition on chisel tillage erosivity. J. Soil Water Conserv. 55, 354–363.
38. Van Muysen W., Van Oost K., Govers G. 2006. Soil translocation resulting from multiple passes of tillage under normal field operating conditions. Soil Till. Res. 87, 218–230.
39. Van Oost K., Cerdan O., Quine T.A. 2009. Accelerated sediment fluxes by water and tillage erosion on European agricultural land. Earth Surf. Process. Landforms 34, 1625–1634.
40. Van Oost K., Govers G. 2000. WATEM, online manual. Catholic University of Leuven. http://www.kuleuven.ac.be/facdep/geo/fgk/leg/pages/downloads/WaTEM/.
41. WatemHome.htm.

42. Van Oost K., Govers G., Van Muysen W., Quine T.A. 2000. Modeling Translocation and Dispersion of Soil Constituents by Tillage on Sloping Land. Soil Sci. Soc. Am. J. 64, 1733–1739.
43. Van Oost K., Govers G., Van Muyssen W. 2003. A process-based conversion model for Caesium-137 derived erosion rates on agricultural land: an integrated spatial approach. Earth Surf. Process. Landforms 28, 187–207.
44. Van Oost K., Van Muysen W., Govers G., Deckers J., Quine T.A. 2005. From water to tillage erosion dominated landform evolution. Geomorphology 72, 193–203.
45. Verheijen F.G.A., Jones R.J.A., Rickson R.J., Smith C.J. 2009. Tolerable versus actual soil erosion rates in Europe. Earth-Science Reviews 94, 23–38.
46. Vieira D.A.N., Dabney S.M. 2011. Modeling edge effects of tillage erosion. Soil Till. Res. 111, 197–207.
47. Walling D.E., He Q., Appleby P.C. 2002. Conversion models for use in soil-erosion, soil-redistribution, and sedimentation investigations.. *In:* Zapata F. (ed.) Handbook for the assessment of soil erosion and sedimentation using environmental radioactivity. Kluwer Academic Publ., Dordrecht, the Netherlands. 111–164.
48. Zgłobicki W. 2002. Dynamika współczesnych procesów denudacyjnych w północno-zachodniej części Wyżyny Lubelskiej. Wyd. UMCS, Lublin.
49. Zhang J.H., Lobb D.A., Li Y., Liu G.C. 2004. Assessment for tillage translocation and tillage erosion by hoeing on the steep land in hilly areas of Sichuan, China. Soil Till. Res. 75, 99–107.
50. Zhang J.H., Su Z.A., Nie X.J. 2009. An investigation of soil translocation and erosion by conservation hoeing tillage on steep lands using a magnetic tracer. Soil Till. Res. 105, 177–183.