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TILLAGE EROSION, DESCRIPTION AND PROCESS OF

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INTRODUCTION

Tillage erosion is a problem that has been present since the dawn of cultivation. The problem has intensified with increased tillage speed, depth, and size of tillage tools, and with the tillage of steeper and more undulating lands. Evidence of tillage erosion is commonly observed as a difference in soil color between hilltops and adjacent lowerslope positions. Tillage erosion is defined by the Soil Science Society of America as the downslope displacement of soil through the action of tillage. It is easy to visualize that when tillage operations are conducted in the upslope direction, forward soil movement will be less than when conducted in the downslope direction (Fig. 1). This difference in soil translocation distance is a function of gravity. Assuming that tillage direction occurs equally often in the upslope and downslope directions, then a net downslope displacement of soil will take place. However, it is not an easy matter to move from this simple concept to one that suggests that soil loss from hilltops in undulating landscapes due to soil translocation by tillage can exceed levels that would be considered sustainable for crop production.

Tillage erosion has often been described in qualitative rather than quantitative terms. Evidence of the mass downslope movement of soil by tillage has been present for years. One example frequently cited comes from the Palouse region of the Pacific Northwest of the United States (1) where soil banks, 3 to 4 m high, have developed at fenceline locations on steep sideslope. These soil banks are the result of moldboard plowing, where the tillage above the fenceline turned the furrow slice toward the fenceline, and tillage below the fenceline turned the furrow slice away from the fenceline. In studies designed to measure the effect of soil variability across landscapes on crop production potentials, tillage has been implicated as the cause for observed downslope soil movement and an increase variability of soil properties (2, 3).

Examination of stereoscopic aerial photographs taken in 1947 and 1991 in the Loam Belt of Belgium showed a severe surface lowering on the top of the hillslopes and on hillslope convexities. Deposition occurred on the lowermost parts of the hillslope in hillslope concavities, and in topographic-defined convergence lines. The observed pattern differed markedly from that expected from water erosion processes, indicating that soil redistribution was dominated by tillage operations (4).

DETERMINATION OF TILLAGE EROSION

A simple linear regression of the form $Y = a + b(S)$ has been developed (5, 6), which describes the relationship between slope gradient (S) and mean soil translocation distance (Y) in the direction of tillage. Slope gradients were considered positive when tilling upslope, and negative when tilling downslope. Expanding on this relationship, it has been proposed (6) that tillage translocation could be considered a diffusion-type geomorphological process, similar to rainsplash and soil creep, and characterized by a single constant, the tillage transport coefficient (k).

$$\mathrm{k} = -D\rho_b B$$

where D is the depth of tillage (m), ρ_b is the soil bulk density (kg m^{-3}), and B is the slope of the linear regression equation of the relationship between soil displacement (m) and slope gradient (m m^{-1}). Using this relationship, the unit soil transport rate in the direction of tillage (Q_s) at any specific point in a field can be calculated as

$$Q_s = \mathrm{k}S$$

where S is the slope gradient (m m^{-1}). Representative tillage transport coefficients (k-value) for moldboard plow tillage have ranged between 230–330 kg m^{-1} (6). Commonly, agricultural fields undergo a series of tillage operation resulting in k-values of 400–600 kg m^{-1}.

It is not possible to directly calculate soil erosion using Q_s, since this value essentially represents a soil flux rate at a cross section for a specific tillage operation or series of operations. However, soil loss or gain will result when, for an elementary slope segment of unit width, the incoming flux is different than the outgoing flux:

$$E = (Q_s, \mathrm{in} - Q_s, \mathrm{out})/\mathrm{X}$$

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Fig. 1 Relative soil displacement distances when the thrust is upslope vs. downslope.

where E is the tillage erosion rate ($\mathrm{kg\,m^{-2}}$) and X is the length (m) of the elementary slope segment under consideration. Since Q_s is directly proportional to the slope gradient, soil loss or gain will be proportional to the change in slope gradient. 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 transport rate. Conversely, soil deposition will take place in concave slope positions in the foot and toeslope positions. When slope gradients between adjacent elemental slope segments are equal, irrespective of their magnitude, no net soil loss or gain takes place because the Q_s in equals Q_s out. Thus, in backslope positions where slope gradients are commonly the greatest, exhibiting the greatest soil transport rate, net soil loss or gain will be minimal provided slope gradients remain constant. Therefore, the rate of soil gain or loss will depend on the unit transport rate and the degree of change in slope gradients:

$$E = \Delta Q_s / X$$

The magnitude of soil erosion rates by tillage vs. water is affected by many variables, i.e., topography, rainfall intensity, tillage intensity (depth and frequency), and land use. Examination of the relationship between a range of topographic parameters and ^{137}Cs-derived erosion rates, from fields in the United Kingdom (7), showed that the highest correlation was between erosion rate and landscape curvature at four of the five sites investigated. These results were not consistent with the dominance of water erosion, where slope angle and upslope lengths, or areas, are the primary influences. In a study comparing the roles of tillage and water erosion on landform development on agricultural land in Belgium (8), it was suggested that if water erosion were the dominant process, the landscape would be characterized by increased incision of the concavities and convergent waterways. A gradual increase in slope angles on upland convex slopes was also noted. In contrast, tillage produces maximum erosion on convex slopes, leading to reduced slope angles and infilling of concavities and hollows. The pattern of landform development observed was an infilling of the slope concavities and convergent waterways by sediment displaced through tillage that more then compensated for the lower-frequency, but more visible, rill and gully incision. The pattern indicates, that despite high susceptibility of the area to water erosion, landform development in this agricultural landscape is currently dominated by tillage erosion processes. These processes result in a reversal of the expected landscape evolution, with a gradual obliteration of topographic features. Other studies have indicated that tillage erosion rates are of the same order of magnitude as water erosion (9, 10).

EFFECTS OF TILLAGE EROSION

The tillage-transport coefficient (k-value) is a measure of the mean distance a mass of soil per unit width is moved by tillage, in a specified direction relative to the direction of tillage. The soil mass is translocated in the forward direction (parallel to the direction of tillage), but is also translocated in the lateral direction (perpendicular to the direction of tillage). Determination of k-values has mostly been in the forward direction. Using the mean displacement distances does not fully describe soil translocation, however. To illustrate, a single pass with a chisel plow may move 70 kg of soil forward per meter width of tillage. The mean forward displacement of this 70 kg of soil may be 40 cm, but significant quantities of soil may be moved as little as 5 cm or as much as 300 cm. Soil displacement will vary across the width of a tillage implement because of the spacing and arrangement of the individual tillage tools. This variation in distance over which soil is translocated is important since it affects the distance that soil constituents (amendments and contaminants) are dispersed or mixed by tillage.

The rate of soil loss by tillage erosion within topographically complex landscapes is several times more than is considered sustainable for crop production. Soil loss on a convex slope position in the Ontario Province of Canada was estimated to be $54\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ (11). Estimates made using resident ^{137}Cs indicate that between 70% and 100% of soil lost on convex slope positions, is the direct result of tillage erosion (12). Crop yield reductions of 40% to 50% have been associated with these eroded landscape positions throughout southwestern Ontario (13).

Although tillage erosion can result in considerable soil loss and accumulation within fields, soil is not directly lost from fields by tillage erosion. However, tillage erosion exposes subsoil material on upperslope positions, which may become more susceptible to wind and water erosion. Furthermore, the redistribution of soil by tillage erosion

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delivers topsoil to areas of concentrated overland water flow on both the microtopographic scale (i.e., rills) and the macrotopographic scale (i.e., convergent landforms) (11, 14). As such, tillage erosion acts as a delivery mechanism of soil, which is then subject to water erosion.

Soil translocation by tillage produces maximum erosion at abrupt convex slope positions, causing a reduction in slope angles, and an infilling of hollows, resulting, over time, in a gradual obliteration of topographic features. As tillage erosion proceeds, the erosion process occurs over an increasingly larger area. In contrast, when water erosion is the dominant process, the landscape is characterized by increased incision of concavities and ephemeral gullies. A gradual increase in slope angle on convex slope positions also occurs.

CONCLUSIONS

Tillage erosion is directly proportional to the degree and scale of topographic complexity. Soil conservation measures that do not include a reduction in tillage erosion will not be effective in controlling soil loss on upperslope landscape positions of cultivated agricultural lands. To reduce soil loss caused by tillage erosion, frequency, tillage intensity (speed and depth), and the size of tillage implements must be reduced.

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