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Tillage Erosion: An Overview

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Abstract: Soil redistribution by tillage is becoming a recognized soil erosion process. Landscapes subject to tillage erosion are topographically complex or have a high number of field boundaries. Tillage erosion contributes to the evolution of landscape heterogeneity through creation of distinct landforms and the relatively rapid redistribution of soils from upland positions to depressions. The resultant variability in soil properties has an important effect on crop production. Our objective is to provide a basic understanding of tillage erosion by describing the tillage erosion process and to discuss the effect of tillage erosion on soil properties and soil productivity, and interaction with water erosion. A brief discussion is included on the subject of future research needs. A soil transport coefficient (k) has been determined as $k = -D\rho b\beta$; where D is tillage depth (m), ρb is the soil bulk density (kg m^{-3}), and β is the slope of the linear regression equation of the relationship between soil displacement and slope gradient. This k-value effectively describes soil transport as a function of slope gradient for a variety of tillage operations; however, the gain or loss in soil mass at any point on the landscape is proportional to hillslope curvature. That is, soil loss from tillage operation will take place on convexities and upper field boundaries, while soil deposition occurs on concavities and lower field boundaries. Soil loss from tillage operations can commonly be greater than what is considered sustainable. As soil is removed from upslope field boundaries or convex slope positions, subsurface soil horizons become exposed. The exposure and subsequent dispersion of this subsoil material, in addition to soil accumulation at lower slope positions, alters soil properties and introduces greater variation in soil properties over the landscape. The recognition of soil translocation by tillage and its subsequent effect on soil properties and variability presents considerable challenges. Soil conservation strategies must be broadened to include tillage erosion to be fully effective.

Key words: Erosion, soil translocation, soil variability, sustainability.

Soil translocation and redistribution in agricultural fields due to the direct action of tillage results in an increase in soil variability and an overall decrease in soil productivity. Tillage erosion is directly related to landscape characteristics. Landscapes subject to tillage erosion are topographically complex or have a high number of field boundaries. Tillage erosion contributes to the evolution of landscape heterogeneity through creation of distinctive landforms, such as lynchets, terraces, and field boundary steps, and through progressive, but relatively rapid

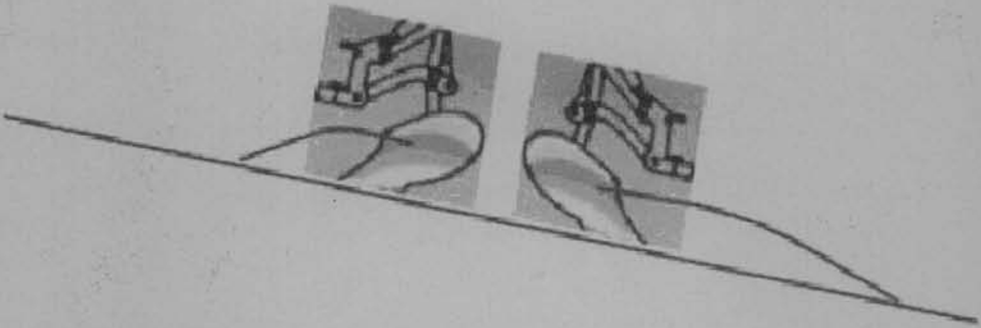

Fig. 1. Relative soil displacement distances when thrust is upslope versus downslope.

redistribution of soil from uplands to depressions. The resultant variability in soil properties has an important effect on crop production.

Evidence of tillage erosion can commonly be observed as the difference in soil color between hilltops and adjacent lower slope positions. The problem has been intensified with increased tillage speed and depth, increased size of tillage tools, and with the tillage of steeper and more undulating lands. 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, it is logical that a net downslope displacement of soil will take place.

Tillage erosion has often been described in qualitative rather than quantitative terms. Evidence of mass downslope movement of soil by tillage has been present for years. One frequently cited example comes from the Palouse region of the Pacific Northwest of the United States (Papendick and Miller, 1977) where soil banks, 3 to 4 m high, have developed at fenceline positions on steep slopes. The fenceline represents a zone of zero soil flux from tillage, i.e., soil does not move through the fenceline. As soil is moved towards the fenceline from above, and away from the fenceline from below, a field border develops. This soil accumulation and removal at field borders can be fairly rapid, leading to development of soil banks several meters high over a time period of a few decades when soil is consistently turned downslope during tillage.

The apparent truncation of hilltops and infilling of historical gullies in southwest France did not follow the pattern expected from water erosion processes and was best explained by long-term downslope soil movement from tillage (Revel and Guiresse, 1995). 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 hillslopes and on hillslope convexities. Deposition occurred on the lowermost parts of the hillslope concavities and in topographic convergence lines. The observed pattern differed markedly from that expected from water erosion, indicating that soil redistribution was dominated by tillage operations (Vandaele *et al.*, 1995).

Description of Tillage Erosion Process

A simple linear regression of the form $Y = a + b(S)$ has been developed (Lindstrom *et al.*, 1992; Govers *et al.*, 1994) where a and b are the regression constant and coefficient, respectively, that describe the relationship between slope gradient (S) and the mean soil translocation distance (Y) in the direction of tillage. Expanding on this relationship, Govers *et al.* (1994) have proposed that tillage translocation could be considered as a diffusion-type geomorphological process similar to raindrop splash and soil creep and characterized by a single constant, the tillage transport coefficient (k):

$$k = -D\rho_b\beta$$

where,

D is the depth of tillage (m), ρb is the soil bulk density (kg m^{-3}), and β 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 average annual downslope soil transport rate (Qs), assuming that the tillage direction alternates between up- and downslope tillage, at any specific point in the field can be calculated as:

$$Qs = kS$$

where,

S is the slope gradient (m m^{-1}). Representative tillage transport coefficients (k-value) for moldboard plow tillage range between 230 and 330 kg m^{-1} (Govers *et al.*, 1994), roughly two to three orders of magnitude greater than what would be expected from soil creep or raindrop splash. Commonly, intensively tilled agricultural fields undergo a series of tillage operations, resulting in k-values of 400 to 600 kg m^{-1} or greater.

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

$$E = (Q_{s,}\text{in} - Q_{s,}\text{out})/X$$

where,

E is the tillage erosion rate (kg m^{-2}), and X is the length (m) of the elementary slope under consideration. Since Qs 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 slope positions, 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 gradient, no net soil loss or gain takes place because Qs,in equals Qs,out. Thus in backslope positions where slope gradients are commonly the greatest, exhibiting the greatest soil transport rate, no net soil loss or gain is observed provided adjacent slope gradients remain equal. Therefore, the rate of soil gain or loss will depend on the unit transport rate and the degree of change in slope gradients.

In less mechanized tillage system, animal power or hand labor, it is common to always direct soil movement towards the downslope direction. This is done to conserve energy. The k-values for animal power or hand labor is less than mechanized tillage, but when the direction of tillage is always downslope an additional constant must be added to account for the unidirectional tillage. Quine *et al.* (1999) concluded that net downslope soil translocation by animal powered tillage always in the downslope direction may exceed those associated with mechanized agriculture.

Measured k-values for individual tillage operation and a series of tillage operations using mechanized equipment, animal power, and hand labor reported in the literature are shown in Table 1. Variations in k-values for similar tillage operations and tools are present. Many factors may be responsible for this variation, including tillage tool and power match, equipment design, soil condition, and depth and speed of operation. Van Muysen *et al.* (2000) reported on the effect of tillage depth, speed, and soil condition on tillage erosivity and showed that the tillage transport coefficient (k-value) increased substantially when the soil was in the unconsolidated state as compared to the consolidated state.

Tillage Erosion and Soil Properties

Lindstrom *et al.* (1992) reported a sustained soil loss of 30 t ha^{-1} y^{-1} from a convex hillslope in southwestern Minnesota from annual moldboard plowing. Lobb *et al.* (1995) reported a soil loss rate of 54 t ha^{-1} y^{-1} from shoulder positions in southwestern Ontario from a moldboard plow, tandem disc (two passes), and a C-tine cultivator. Clearly soil loss rates of this magnitude are not sustainable. Soil loss rates of this magnitude will rapidly expose the underlying subsoil that generally is less productive or desirable on convex slope positions and at upslope field borders. In time the properties of the tilled layer will be determined by the properties of the original subsoil in convexities and upslope field borders. As tillage erosion continues the area of exposed subsoil expands. Subsequent tillage transports the exposed subsoil downslope, which mixes with the original topsoil material in the tilled layer. As this process continues with continued tillage, the tilled layer over a large portion of the landscape will have properties more associated with the subsoil horizons than properties associated with the original topsoil (Fig. 2).

The tillage transport coefficient (k-value) represents the mass of soil per unit width that is moved by tillage across a point on the landscape in a specified direction relative to the direction of tillage. The k-value is dependent on the mean displacement distance of soil as affected by slope gradient. The soil mass is translocated forward in the direction of tillage, but is also translocated in the lateral direction. Determination of k-values has mostly been done in the forward direction. Using the mean displacement distances does not fully describe soil translocation however (Lobb and Kachanoski, 1999). For example, 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

Table 1. Comparison of tillage transport coefficients (k-value), available in, or calculated from the literature, for different implements, tillage directions, tillage speed and tillage depth. (after Van Muysen et al., 2000)

Source	Tillage depth (m)	Tillage speed ($m\ s^{-1}$)	Implement	k-value (kg m^{-1} per tillage operation)
Up- and down-slope tillage				
Govers *et al.* (1994)	0.15	1.25	Chisel	111
Govers *et al.* (1994)	0.28	1.25	Moldboard	234
Lindstrom *et al.* (1992)[a]	0.24	2.1	Moldboard	330
Lobb *et al.* (1995)[b]	0.15	1.1	Moldboard	184
Lobb *et al.* (1995)[b]	0.11	1.12	Moldboard + 2 disc + cultivator	473-734
Lobb and Kachanoski (1999)	0.17	2.66	Chisel plough	275
Lobb and Kachanoski (1999)	0.23	1.71	Moldboard	346
Lobb and Kachanoski (1999)	0.17	0.84	Tandem disc	369
Lobb and Kachanoski (1999)	0.15	1.92	Field cultivator	13
Poesen *et al.* (1997)	0.16	0.65	Duckfoot chisel	282
Quine *et al.* (1999)	0.19	2.3	Duckfoot chisel	605-660
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard	425
Turkelboom *et al.* (1999)	0.08	n.a.	Manual tillage (hoe)	77
Van Muysen *et al.* (1999)	0.33	0.5	Moldboard (pre-tiled soil)	254
Van Muysen *et al.* (1999)	0.15	0.75	Moldboard (fallow soil)	70
Controur tillage				
Lindstrom *et al.* (1992)[a]	0.24	2.1	Moldboard	363
Montgomery *et al.* (1999)	0.23	1.0	Moldboard	110
Poesen *et al.* (1997)	0.14	0.65	Duckfoot chisel	139
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard	710
Thapa *et al.* (1999)[b]	0.20	n.a.	1 Moldboard + 2 ridger	260
Thapa *et al.* (1999)[b]	0.20	n.a.	4 Moldboard + 1 harrow	424-645
Thapa *et al.* (1999)[b]	0.20	n.a.	2 Moldboard + 1 harrow	299-348

n.a.: data not available; a: Data obtained from Govers *et al.* (1994); b: Reported *k*-values for totals for the sequence of tillage operations given. Tillage depth and speed are average for the tillage sequence.

Fig. 2. Intensively tilled landscape showing exposed subsurface horizons on convex slope positions. Annual moldboard plowing and secondary spring tillage has removed the original topsoil, exposing the underlying Bk horizon, resulting in increased field variability and overall reduction in crop productivity.

(Lobb *et al.*, 2000). Soil displacement will vary across the width of a tillage implement due to the spacing and arrangement of the individual tillage tools. This variation in distance over which soil is translocated is important as it affects the distance that soil constituents (amendments and contaminants) are dispersed or mixed by tillage.

Sibbesen *et al.* (1985) demonstrated the significance of tillage translocation and the mixing of soil within the till-layer by predicting the rate and extent of cross-contamination of soil amendments by tillage translocation in long-term fertility research plots on level land. Lobb and Kachanoski (1999) have expanded on this concept by using various functions to describe the distances soil is displaced. In this analysis, an exponential function provided superior results over a step or linear-plateau function in describing the magnitude of translocation and the redistribution pattern of the soil in the tilled layer. In both cases, dispersion of a finite amount of known tracer by tillage was rapid and extended over several meters within a short time period (years). Van Oost *et al.* (2000) measured movement of sand from a sand outcrop situated at the upper slope boundary a distance of 45 m downslope in a field that had been cultivated for approximately 130 years. Soil dispersion by tillage, direction of tillage, and topography were factors considered in development of a model to describe the progression of sand movement downslope. Best correlation for dispersion of the sand required consideration of soil transport by water; however, soil translocation and dispersion by tillage accounted for the major portion of the redistribution of the sand.

Exposure of underlying subsoil to the surface and subsequent redistribution over the landscape by tillage modifies existing soil properties. Commonly the structural stability of the underlying subsoil is lower and combined with lower inherent soil organic matter content makes the soil more vulnerable to wind and water erosion. Furthermore, the redistribution of soil by tillage erosion delivers soil to areas of concentrated overland flow on both the microtopograhic scale, i.e., rills, and the macrotopograhic scale, i.e., convergent landforms (Lobb *et al*., 1995; Govers *et al*., 1996). As such, tillage erosion acts as a delivery mechanism of soil, which is then subject to water erosion. Water erosion is greatest along the central axis of hillslope concavities or draws where a large volume of surface runoff is concentrated, commonly leading to ephemeral gullies. This is also the zone of deposition by tillage erosion. While soil is not moved past field boundaries by tillage erosion, when soil is deposited in zones of concentrated runoff, it becomes subject to field loss.

The balance between deposition and removal depends on the relative intensity of the two processes and landscape morphology. Deposition by tillage will increase with increasing concavity; soil removal will increase with increasing slope gradient and upslope water contributing area. Thomas and Welch (1988) in the southern Great Plains, USA, using stereoscopic techniques found that more soil material was moved into two major ephemeral gullies by tillage than was removed by water erosion.

Tillage Erosion and Water Erosion

The magnitude of soil erosion rates by tillage versus water is affected by many variables, i.e., topography, rainfall intensity, tillage intensity (depth and frequency), and land use. After examining the relationship between a range of topographic parameters and ^{137}Cs-derived erosion rates, Quine and Walling (1993) 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. Quine and Walling *et al*. (1994) compared the roles of tillage and water erosion on landform development on agricultural land in Belgium. If water erosion was the dominant process, they hypothesized that the landscape would be characterized by increased incision of the concavities and convergent waterways and a gradual increase in slope angles on upland convex slopes. 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 slope concavities and convergent waterways by sediment displaced through tillage that more than compensated for the less frequent but more visible rill and gully incision. Overall, the pattern indicates that despite the high susceptibility of this area to water erosion, landform development in this agricultural landscape is currently dominated by tillage erosion processes. A gradual obliteration of topographic features was found, rather than the expected landscape evolution if water erosion was the major contributing agent for landform development.

Quine *et al.* (1999) differentiated between erosion processes (tillage and water) at three field sites in China, Lesotho, and Zimbabwe. Tillage systems ranged from manual to mechanized. Soil movement rates from tillage translocation were determined through an iterative process to determine the best-fit k-value explaining the loss of ^{137}Cs at upper field boundaries and landscape positions where soil movement due to water erosion would be minimal. Using the best-fit k-value and water erosion equations the predicted soil movement levels were highly correlated with observed ^{137}Cs redistribution. In these analyses, soil movement by tillage was responsible for approximately 50% of the observed soil erosion measured in the three field situations.

Tillage Erosion and Soil Productivity

The impact of tillage erosion on soil productivity is primarily related to soil removal from a specific landscape position and deposition in another part of the landscape. Many of the causes of changes in soil productivity attributed to wind and water erosion also apply to tillage erosion. Lal (1988) lists several direct effects of soil erosion on crop yield, including a reduction in rooting depth, loss of plant nutrients, loss of available plant water, loss of land area, and damage to seedlings. Of these, tillage erosion acts on soil productivity through the first three: loss of effective rooting depth, loss of plant nutrients, and loss of plant-available water. Li and Lindstrom (2001) report changes in soil quality parameters, i.e., soil organic matter, plant-available nutrients, and bulk density, in terraced fields and along a steep cultivated hillslope in the Loess Plateau of China and attribute the changes in soil quality to soil deposition by tillage. In the terraced fields, soil organic matter content was lowest at the upper terrace boundaries and increased towards the lower terrace boundary. Soil bulk density was highest at the upper terrace boundary and lowest at the lower terrace boundary. In the steep cultivated hillslope, soil organic matter content and available plant nutrients were observed to increase in concave landscape position, most notably in the foot and toeslope areas, but also in the mid-backslope position where a discernable concave slope was present.

In the Philippines uplands, Thapa *et al.* (2001) measured changes in nutrient gradients on a steep hillslope (16 to 22%) and on terrace systems within a four-year-period with animal tillage systems. The extractable P concentration gradient became steeper for management systems utilizing grass barriers, with the highest concentration at the base of the terrace. Thapa *et al.* (1999) estimated that as much as 40% of the cropped area between terraces might eventually be degraded physically, chemically, or biologically if moldboard plowing continues. Downslope soil movement in the upland portion of the terrace was 42 t ha^{-1} y^{-1}, exposing an acidic subsoil with high Al saturation. In narrow spaced (5 m) terrace systems on steep uplands in Rwanda, Lewis (1992) describes the techniques used by local farmers to partially maintain fertility on the upslope portion of the terraces. The grass terrace was annually undercut to add nutrient-rich soil to the severely degraded soil that has developed from downslope soil movement with hand tillage operations.

Schumacher *et al.* (1999), using a tillage erosion model (Lindstrom *et al.*, 1992) and a water erosion model (Flanagan and Nearing, 1995) evaluated the effects of erosion patterns on soil property distribution on a landscape representative of glacial till landforms common to eastern South Dakota and western Minnesota. Summit, shoulder, backslope, footslope, and toeslope positions were represented in the landscape with representative soil series for each landscape position. The resulting changes in soil properties of the root zone, due to movement by the two eroding processes, were evaluated for each landscape position for change in productivity using a productivity model (Piece *et al.*, 1983).

This simulation of soil redistribution within the soil catena resulted in spatial changes in soil productivity due to loss or gain in topsoil thickness. An evaluation of productivity based on the simulated redistribution of soil on the hillslope showed an increase in spatial variability of soil productivity in the shoulder, backslope, and upper footslope positions. The net effect of soil redistribution from the combined effects of tillage and water erosion was a decrease in crop productivity in the shoulder and upper backslope positions and an increase in crop production potential in the footslope position. The increase in the footslope position did not compensate for the loss in crop production potential in the shoulder and upper backslope positions.

Research Needs

The most effective way to arrest tillage erosion and its adverse impacts is to eliminate tillage. However, tillage is an integral part for most forms of crop production. At a minimum, tillage is required for placement of seeds and nutrients. Tillage may be required for crop management and harvesting, i.e., root crops such as potatoes. Although the intensity of tillage has been dramatically reduced in many regions of the world over the past couple of decades, no-till or zero-till-cropping systems account for only a minor percentage of total cropped land in most parts of the world. The challenge will be to develop equipment and practices that provide the desired effect of tillage while minimizing soil erosion by wind, water, and tillage.

While some degree of tillage is necessary, tillage frequency and intensity (speed and depth), implement size and design, tillage pattern, and soil condition are factors that may be adjusted to minime tillage erosion. Data from Van Muysen *et al.* (2000) show the additive effects of increased speed and depth to the tillage transport coefficient for a chisel plow. Additional data from Van Muysen *et al.* (1999) showed an increase in the tillage transport coefficient with moldboard plowing from 70 kg m^{-1} for a grass fallow consolidated soil to 254 kg m^{-1} on a pre-tilled unconsolidated soil condition, suggesting the increase in soil erosivity that will occur with secondary tillage. Under these conditions local maximum erosion rates increased from approximately 8 to 35 Mg ha^{-1} from the consolidated to unconsolidated soil condition.

Tillage equipment should be designed with consideration for tillage translocation and tillage erosion. Tool geometry, arrangement, and combination should not only create a suitable seedbed, incorporate residue, etc., they should also minimize the amount of soil translocated and minimize the potential for variation in translocation. The size of tillage implements in relation to landscape size may be an important consideration. Tillage implements that are very long and/or very wide have the potential to increase tillage erosion through a planing effect over variable topography. Variability in soil translocation has the potential to increase with tillage implements equipped with multiple ranks over a single ranked design. Systematic research will be required to assess these relationships.

Simulation models can identify lands that are sensitive to tillage erosion that may require changes in land management or, in serious cases, changes in land use. Presently the models that have been developed only consider soil translocation in one direction, forward or lateral. De Alba (2001) has developed a two dimensional model for the moldboard plow representing a more accurate presentation on how soil truly moves with tillage. Fully integrated soil erosion models must be developed to understand the synergy between erosion processes. Govers *et al.* (1996), Quine *et al.* (1999), and Schumacher *et al.* (1999) have used water and tillage erosion models in tandem. To fully understand and predict soil erosion potentials, wind, water, and tillage erosion processes should be integrated into a single model.

Soil translocation downslope due to tillage action has the potential to alter soil profile characteristics. As subsoil is exposed to the surface with tillage erosion, subsoil material will be dispersed over the landscape. De Alba (1999) in his Ph.D. thesis presents a hypothesis on changes in soil horizon sequences that would occur due to tillage erosion (Fig. 3). Ellis (1938) proposed a similar sequence of change while observing differences in horizon sequence of short-term cultivated and non-cultivated soils in the Canadian Province of Manitoba. These changes in profile characteristics will undoubtedly alter soil productivity potentials and vulnerability to wind and water erosion, but will also have an effect on other soil physical, chemical, and biological properties and processes. This is a relatively unexplored area of research that merits much attention in the future.

The recognition of tillage translocation and tillage erosion, and their significance, present considerable challenges and opportunities for tillage researchers and practitioners. Soil conservation strategies must be broadened to include tillage erosion and they must be fully integrated. To undertake this approach in soil conservation requires research on many aspects of tillage. These challenges and opportunities are equal in magnitude to those placed on wind and water erosion.

Conclusions

Tillage erosion, the progressive downslope movement of soil through the action of tillage operations, is a serious problem that needs to be considered during the development of conservation management plans. Tillage erosion is directly proportional to the degree and scale of topographic complexity. The magnitude of soil translocation from upslope positions, either convex slopes or upper terrace borders, can result in soil loss, which can greatly exceed levels that would be considered sustainable. Although soil is not directly lost from fields by tillage erosion, it is moved from upslope or convex slope positions and deposited at field or terrace borders and

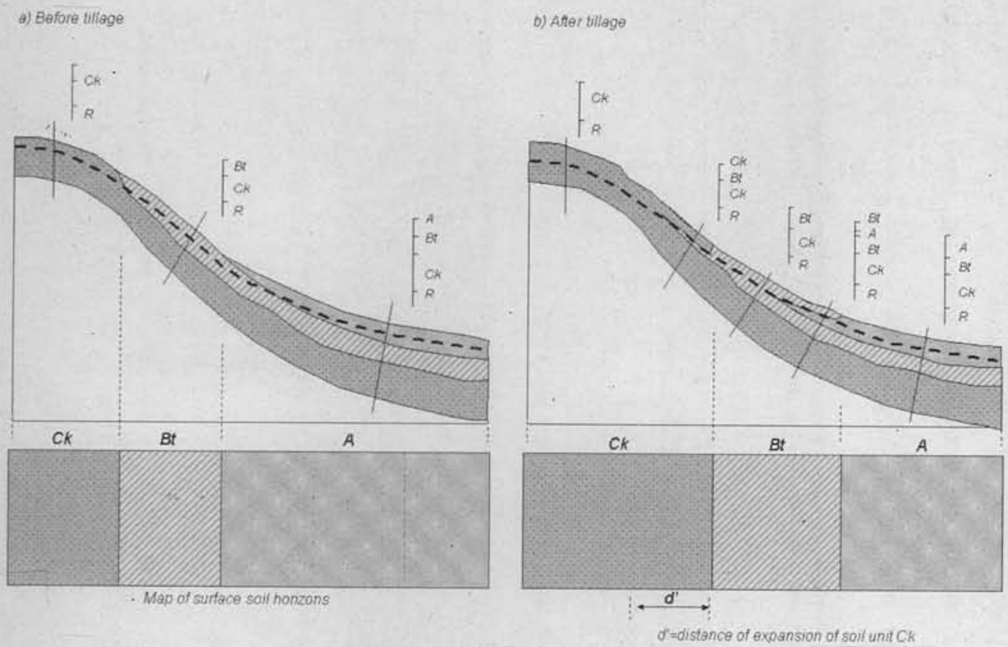

Fig. 3. Effects of soil redistribution by tillage on soil profile morphology and soil landscape variability, showing catena transformation due to tillage erosion.

concave slope positions. The interactions between tillage and water erosion require that both processes be considered. The net effect of soil erosion, either tillage or water erosion, is an increase in field variability and a reduction in crop production potential.

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Dryland Degradation by Wind Erosion and its Control

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Abstract: Global population growth is expected to impose an increasing pressure on agricultural production in the world's drylands, which cover approximately 41% of the continental area. The land resources in drylands are severely threatened by soil degradation, with wind erosion being one of the major degradation processes. It causes sedimentation at undesired places, crop damage by sand blasting and burial, deterioration of soil structure, a loss of soil fertility, and it affects the water economy in the topsoil. On drylands in developing countries, adequate wind erosion control is currently not achieved due to poor socio-economic conditions, low crop biomass production, crop competition and management constraints. A potential solution is to make use of the natural dryland vegetation of scattered trees and shrubs. But, more research is needed to better understand the effects of scattered vegetation on wind speed and erosion, as well as on particle deposition and accumulation. This ultimately should lead to models that can help develop location-specific wind erosion control strategies.

Key words: Drylands, degradation, wind erosion, erosion control, natural vegetation.

World-wide population growth has resulted in an increasing demand for food, fibre, fodder, and fuelwood. From the beginning of agriculture until approximately 1950, increased agricultural production resulted almost entirely from an expanded cropland base. Since 1950, however, the yield per unit of land area for major crops has increased dramatically (Stewart and Robinson, 1997). The main reasons for the higher production are mechanization, large-scale fertilizer application, control of pests and diseases, expansion of the irrigated area, and development of high-yielding crop varieties.

The improved agricultural practices have been particularly applied on land with favorable topography, soil and climate. On marginal land, increases in production per unit land area have been significantly lower, and sometimes even negative. For instance the increased food production in semi-arid West Africa during the past decades has mainly come from expansion of the cropland area into more marginal land instead of higher yields per unit of land. At the same time the fallow periods have become too short to allow natural restoration of soil productivity. As a consequence, yields per unit land area have declined (Klaij and Hoogmoed, 1989). Apparently, West African farmers were not able to adopt the production-stimulating practices that have been so successful in other regions. The main reason is the poor socio-economic conditions that reinforce the tendency

Table 1. Distribution of the world's drylands in millions of hectares (UNEP, 1991)

Dryland type	Africa	Asia	Australia	Europe	North America	South America	World total
Hyper-arid	672	277	0	0	3	26	978
Arid	504	626	303	11	82	45	1571
Semi-arid	514	693	309	105	419	265	2305
Dry sub-humid	269	353	51	184	232	207	1296
Total	1959	1949	663	300	736	543	6150
% world total	32	32	11	5	12	8	100
% total global land area	13.1	13	4.4	2	4.9	3.6	41

towards short-term time horizons in production decisions, and arrest investments in land resources (Barbier, 2000).

There are few areas left with favorable environments for further development of high-productivity agriculture. Especially the expansion of irrigated land is expected to be small in the near future. Hence, future increases in agricultural production will more and more rely on rainfed crop production on marginal land. This is especially true for the world's drylands, which cover many of the developing countries where population growth rates are the highest in the world (Rozanov, 1994). Drylands are defined by UNEP (1991) as those lands that have a precipitation over potential evapotran-spiration ratio of less than 0.65. They can be sub-divided into hyper-arid, arid, semi-arid, and dry sub-humid lands. Drylands cover approximately 41% of the continental land area. Two-thirds of the drylands are in Africa and Asia (Table 1).

The arid, semi-arid and dry sub-humid drylands are inhabited and exploited for agricultural production. General characteristics of these drylands are insufficient precipitation, low soil fertility, and a rapid loss of arable land to soil degradation (Stewart and Robinson, 1997). Dregne *et al.* (1991) estimated that 154 million ha (2.5%) of the world's drylands is irrigated cropland, 458 million ha (7.4%) is rainfed cropland, and 4546 million ha (74%) is used as rangeland. They also estimated that 70% of all agriculturally used dryland is subject to some degree of degradation. Rainfed cropland is degraded by wind erosion, water erosion, soil nutrient depletion, and physical deterioration. Rangelands are affected by degradation of vegetation and, to a lesser extent, by wind and water erosion (Dregne *et al.*, 1991).

According to the Global Assessment of Soil Degradation (GLASOD) map (Oldeman, 1994) wind erosion is the most important soil degradation process on drylands, closely followed by water erosion (Table 2). Chemical degradation (nutrient depletion, salinization, alkalinization) is the third soil degradation process. Of least

Table 2. Global and continental extent of water and wind erosion in millions of hectares (Oldeman, 1994)

Continent	Water erosion			Wind erosion		
	Total	Dryland zone	Humid zone	Total	Dryland zone	Humid zone
Africa	227	122	105	186	186	1
Asia	441	165	276	222	206	16
Australia	83	70	13	16	16	0
Europe	114	48	66	42	39	3
N America	106	38	68	40	38	1
S America	123	35	88	42	28	14
World	1094	478	615	548	513	36

importance in drylands is physical soil degradation (compaction, crusting).

Wind erosion occurs mainly in the non-irrigated arid and semi-arid agricultural lands. The aim of this paper is to provide an overview of wind erosion processes in those areas, and also to discuss about its on- and off-site effects, the responsible socio-economic and political factors, the potentials for its control, and the future research strategies.

Wind Erosion Processes

Wind erosion can become a problem whenever the soil is dry, loose and has a sandy texture, the surface is bare or nearly bare, the wind velocity regularly exceeds the threshold for initiation of soil particle movement, and the susceptible area is sufficiently large (Fryrear and Skidmore, 1985; Lyles, 1988). By definition, wind erosion is the removal of soil material, whereas sedimentation is the deposition of wind-blown material. The transport of soil material between erosion and sedimentation can occur in three different modes: saltation, creep and suspension (Fig. 1).

There is no sharp demarcation line between these three modes of particle transport, but there is rather a gradual transition. The largest particles (>500 μm) roll or slide over the surface without loosing contact with the latter, a process known as surface creep or surface traction (Pye and Tsoar, 1990). Smaller particles, between 500 and approximately 50-100 μm, are transported in saltation. Saltating particles jump and bounce over the surface, reaching a maximum height of approximately 1 m, but the main particle mass moves just above the soil surface. When saltating particles fall back to the surface they not only eject other saltation-size grains, but also induce surface creep, reptation (some small-scale saltation with only a limited displacement of grains near the points of impact) and surface deformation. They also cause the raising of dust particles, which are transported in suspension. Suspended particles are kept aloft due to the turbulent nature of the airflow. A distinction is made between short-term and long-term suspension depending on

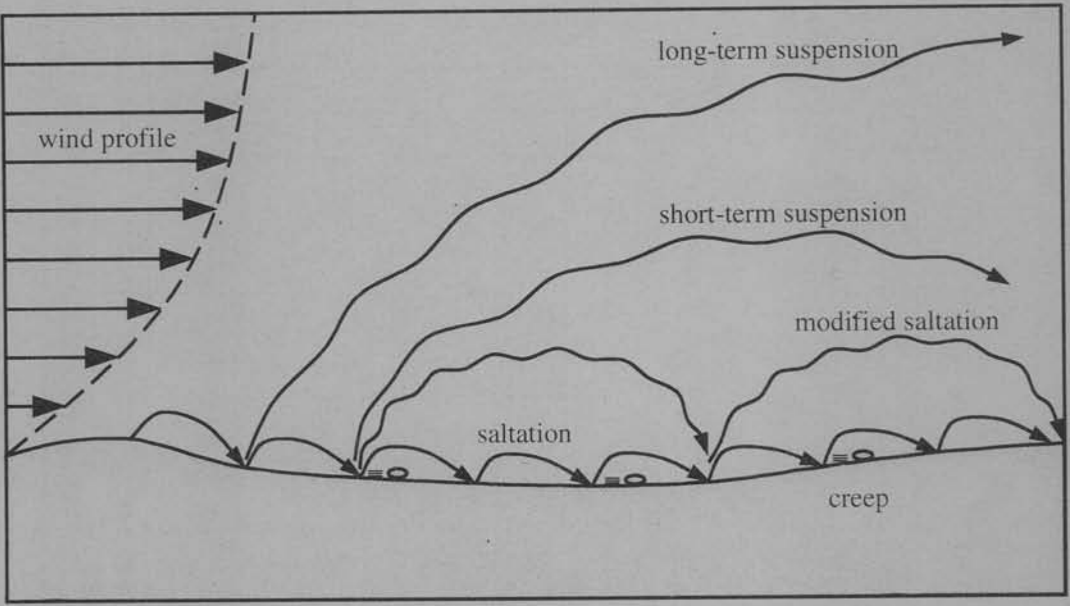

Fig. 1. The processes of wind-blown particle transport.

whether the particles will stay airborne for only a short time (normally a few hours) or longer (days or weeks).

The transition mode between saltation and suspension is known as modified saltation. Trajectories of particles transported in this mode show similarities with typical saltation jumps, but are significantly affected by turbulence. No clear particle size boundaries exist between saltation, modified saltation and suspension although typical saltating particles are normally >100 µm whereas suspended particles are usually <50 µm. The lack of clear boundaries indicates that certain particles may be moved by different transport modes, depending on particle density, wind speed and the level of turbulence in the airflow.

Depending on their way of transport particles may move over a wide range of distances. During a storm, creep can move particles over distances from a few centimetres to several metres; saltating particles travel from a few metres to a few hundred metres, and suspension transport ranges from several tens of metres to thousands of kilometres (Sterk, 1998).

Measurement Techniques of Wind Erosion, Transport and Deposition

Quantification of wind-blown particle transport in the field is difficult because of large temporal and spatial variability in particle mass fluxes (Wilson and Cooke, 1980). At a certain location, the number of transport events differ from year to year, and during a particular year, events vary in duration and intensity, ranging from short-term wind gusts to heavy storms that may persist for days. Wind speed, wind direction and other meteorological parameters may vary during or between events, leading to a wide range in the particle mass fluxes. Moreover, soil erodibility is determined by several variables like soil texture, surface roughness and topography. These variables usually show spatial variability, resulting in spatial differences in soil erodibility and thus in particle mass fluxes as well (Sterk and Stein, 1997).

The spatial and temporal variability of the processes makes quantification of wind erosion a difficult task, though not impossible. Measurement techniques of wind erosion, wind-blown particle transport and deposition can roughly be divided into direct and indirect techniques (Table 3), and are scale-dependent.

Indirect techniques

Indirect techniques such as the ^{137}Cs isotope method (e.g., Chappell *et al.*, 1996) or repeatedly measuring soil surface elevation (Wilson and Cooke, 1980; Gibbens *et al.*, 1993), for example with erosion pins (de Ploey and Gabriëls, 1980) or using the odolite measurements (Warren and Kay, 1987), do not quantify soil particle transport itself, but determine the erosion or sedimentation rate from changes in soil surface elevation or ^{137}Cs concentration. These techniques give point observations with a temporal resolution varying from days to several decades. A problem, however, is that in many areas where wind erosion occurs soils are also subject to water erosion, which makes it difficult to determine the rate of soil loss due to wind erosion alone.

Other indirect techniques that work at larger spatial scales and at similar or larger temporal scales are the use of remote sensing, for instance for tracing sand and dust movement in the Saharan desert (e.g., Mainguet, 1984), the use of aerial photographs (van Reet, 1999) and the description of wind erosion features in geomorphologic studies (e.g., Cornish, 1900; Jawad Ali and Al-Ani, 1983). These latter techniques do not lead to quantitative data on particle transport, but may provide very useful information on spatial patterns, as well as on the relative intensity of the transport processes in the region.

Direct techniques

Erosion and sedimentation, in their turn, can be directly measured using specially designed erosion and sedimentation plots or, in the case of sedimentation, with the help of deposition collectors (Offer and Goossens, 2001). Erosion and sedimentation amounts can also be derived indirectly from airborne sediment concentration gradients near the plots (Goossens *et al.*, 2001), or from the spatial distribution of the amount of sediment transported in the region (by calculating a sediment balance, which is the mass balance between input and output of soil particles; see Mainguet, 1996).

Sediment recording devices can roughly be divided into two groups. The first group consists of catcher-type and filter-type samplers, which are characterized by a relatively low temporal resolution. For instance, sediment catchers continuously trap particles during storms, but the total particle mass flux can only be determined after the storm by weighing the trapped material. The same holds true for filter-type samplers (e.g., Rajot *et al.*, 1996), which suck sediment-laden air through a filter.

Table 3. Indirect and direct measurements of erosion, transport, deposition and accumulation

Technique	Process	Time scale	Areal scale
Indirect measurements			
Erosion pins	Erosion, accumulation	Short-term, medium-term, long-term	Local
Topographic measurements	Erosion, accumulation	Medium-term, long-term	Local, regional
Airborne sediment concentration gradient	Erosion, deposition	Short-term, medium-term	Local
Sediment tracer	Erosion, transport, deposition, accumulation	Short-term, medium-term	Local
Satellite pictures	Transport	Short-term, medium-term, long-term	Regional, continental
Aerial photographs	Transport	Medium-term, long-term	Regional
Description of aeolian features	Transport	Short-term, medium-term, long-term	Local, regional
Sediment dating	Accumulation	Long-term	Local
^{137}Cs measurements	Accumulation	Long-term	Local
Direct measurements			
Erosion plots	Erosion	Short-term, medium-term	Local
Horizontal sediment flux traps	Transport	Short-term	Local
Horizontal sediment flux counters	Transport	Short-term	Local
Deposition traps	Deposition	Short-term, medium-term	Local
Accumulation plots	Accumulation	Short-term, medium-term, long-term	Local

After some time of operation the filter is replaced. Hence, the mass of dust on the filter represents the total mass flux for the period of operation.

The second group of direct samplers are characterized by a high temporal resolution. These samplers continuously record soil particle transport. Devices have been developed that measure saltation transport by detecting particle impacts using microphones (Spaan and van den Abeele, 1991) or a piezoelectric crystal (Stockton and Gillette, 1990). A slightly different technique was used by Janssen and Tetzlaff (1991), who developed a catcher that continuously weighs the mass of trapped saltation particles.

A review of sediment samplers frequently used in aeolian research can be found in two papers by the third author (Goossens and Offer, 2000; Goossens *et al.*, 2000).

Apart from field measurements, simulations in a wind tunnel may be a helpful tool when testing techniques for wind erosion control. In a wind tunnel wind erosion experiments can be performed under controlled conditions, which makes it possible to investigate the role of various parameters affecting the deflation threshold, such as particle size (Horikawa and Chen, 1960; Iversen and White, 1982), the role of roughness elements (Logie, 1982), or the effect of the topsoil's water content (Belly, 1964; Azizov, 1977). However, because of size limitations natural vegetation usually cannot be introduced in the wind tunnel without artificially distorting the boundary layer flow in the tunnel. This puts some constraints on the use of wind tunnels when assessing the role of vegetation in wind erosion control. However, wind tunnel experiments with vegetation (and landscape) at a reduced scale may help detect the areas most vulnerable to, or most protected from, wind erosion. Experiments with terrain models at reduced scale have been very successful with respect to the modeling of the aeolian sediment flow in natural terrain (Offer and Goossens, 1994, 1995).

On- and Off-site Effects

Wind erosion on farm land may be responsible for on-site damage, e.g., damage in the area where the removal of the soil particles takes place. In this area all three modes of particle transport can take place causing different types of damage like soil degradation and physical damage of the crops. Off-site effects can be observed adjacent to the source area as well as at far off distances (Table 4).

On-site effects

Soil degradation in wind-blown areas is primarily caused by the loss of topsoil, which has an impact on the physical and chemical properties of the soil. Creep, saltation and suspension transport have different impacts on soil productivity. Creep particles are large and are nearly devoid of nutrients. Hence, creep transport does not significantly affect soil fertility. Saltation particles contain nutrients at a low concentration, while suspension material is relatively rich in nutrients (Sterk *et al.*, 1996). The selective removal of fine particles, characteristic for wind erosion, results in a deterioration of soil structure. The texture of an actively eroding soil becomes progressively coarser, which negatively affects structure stability and water holding capacity. The chemical soil properties are affected because most plant-available nutrients are located in the top few centimetres of the soil and wind erosion preferentially removes the organic matter and clay, which hold these nutrients (Lal, 1988). The extent of soil degradation caused by wind erosion depends, among other factors, on the texture and fertility of the original soil. Most dramatic

Table 4. A selection of physical and economic harmful effects of wind erosion (after: Riksen and de Graaff, 2001)

Location of effects	Physical effects	Economic effects
On-site		
On the soil	Fine soil and organic material blown away Degradation of soil structure Loss of fertilizers, pesticides	Decrease of soil fertility and production Costs of additional labor for tillage, etc. Replacement costs of agro chemicals
On the crop	Loss of seeds and plants Damage to stem and leaf	Replacement costs of plants and seeds Loss of production
Use of equipment	Damage to machinery Postponement of operations	Increased cost of repair and maintenance Lack of timeliness and loss of production
Off-site		
Adjacent sites	Sand dune formation Sand dune formation Sedimentation in ditches, hedges and on roads	Loss of production land or cost to level out the area Costs of labor for cleaning
At a distance	Eutrophication/damage to nature reserves etc. Dust in residential areas Dust in machinery	Costs of liming, etc. Opportunity costs of cleaning Costs of maintenance and repair

degradation occurs on sandy soils with low organic matter contents, because of their high erodibility, poor structural stability, and low fertility, and often sparse vegetation cover, especially in (semi) arid zones.

Physical crop damage occurs when seedlings suffer from abrasion, or are buried by sand during storms. Abrasion, or sandblasting, damages plants by the scouring effect of saltating sand particles. Damaged plants are more susceptible to sun burning and diseases. Young plants buried during storms suffer afterwards from the weight of the sand, reduced sunlight interception, and high soil temperatures during daytime. Plant damage resulting from impacting and/or accumulating sand ranges from reduced growth and development to a total destruction of the crops (Michels *et al.*, 1995).

Off-site effects

Saltation transports material over limited distances, from unprotected sources towards sinks. For instance, sites with dense vegetation cover trap saltation material coming from surrounding source areas, like arable fields. The fertility status of the vegetated site will then become improved at the expense of decreasing soil productivity in the unprotected, upwind areas. This process can also occur on a smaller scale. Individual obstacles in a field, like shrubs, may trap

Fig. 2. Sandstorms can cause serious harmful off-site effects.

wind-blown material from nearby sources. The micro-dunes resulting from the accumulation of these wind-deposited sediments are known to farmers as having the best productivity after the shrubs have been cut down (Sterk and Haigis, 1998). However, the supply of wind-borne material can also negatively affect the sink areas. Herbicides and pesticides, or the transport of organisms from infected sources, can cause considerable damage to the soil in the sinks.

Sedimentation of wind-blown material may cause dune formation at some distance from the source area. It may also fill drainage ditches and irrigation canals, and can cause blockage of roads (Duncan and Moldenhauer, 1968).

Finally, suspended dust risen from a field may be carried over long distances. Observations of West-African dust crossing the Atlantic Ocean have been repeatedly reported in the literature (e.g., Westphal Toon and Larlson, 1988). Prospero and Carlson (1972) estimated that between 25 and 37 million tons of wind-blown dust cross the Atlantic annually, with even greater amounts deposited in the ocean (Lal, 1988). Also here, settling dust supplies the sinks with various substances that are transported with the dust.

Although soil degradation is one of the major concerns in the dryland regions due to the decrease in crop production and loss of productive farmland, the off-site effects may also be considerable and should be taken into account with the planning of soil conservation strategies. Sand and dust storms can cause disturbance to everyday life (Fig. 2), including air pollution causing health problems, air traffic disturbed by aerosols and reduction of visibility, and sand encroachment on roads, railways and urban structures (Mainguet, 1998).

Table 5. Assessment of the costs of wind erosion

Step	Research on	Output	Scale	Time scale
Identification of fields with high potential wind erosion risk	• Intrinsic soil properties or soil erodibility • Vegetation-cover • Wind shelter	Potential wind erosion risk map	Region	5-10 years
Assessment of actual wind erosion risk	• Crop rotation • Land preparation • Erosion control measures	Actual wind erosion risk map based on land use	Region	Year
Assessment of actual on-site effects	• Change in soil properties • Crop damage	Damage per crop/land management system	Farm or field	Year or event
Assessment of on-site costs	• Costs due to loss of production • Extra production costs • Loss of productive land	Costs per crop or land management system	Farm or field	Year or event
Assessment of off-site costs	• Costs for repair or cleaning	Total costs for the community	Community	Year or event

Assessment of On- and Off-site Effects

The assessment of on- and off-site effects is difficult due to large temporal and spatial variability of the wind erosion process and in many cases the long-term effect of erosion is masked by the use of fertilizers. In fact most of the society does not recognize the slow changes caused by wind erosion (Mainguet, 1998). Therefore, it is important to know the extent of on- and off-site damage for each land-management system in wind erosion risk areas.

Most erosion damage occurs while the soil is bare until a soil cover of at least 30%. The assessment can be divided into five steps as shown in Table 5.

The first two steps can be used to identify the areas where erosion control measures would benefit most. The other steps are needed to get the input data for the costs and benefits of control measures and to give land users and policy makers insight in the financial and economic significance of the wind erosion problem.

There are no standardized research methods for the assessment of on- and off-site costs. The research methods used depend mainly on the research area and research budget. Due to the large temporal and spatial variability one would need at least several years of research to get good insight in the actual costs due to the effects of wind erosion.

Planning of Soil Conservation Strategies

Although the assessment of on- and off-site effects helps to highlight the main areas with an erosion problem, more research is needed to be able to find a sustainable solution to minimize the erosion risk. To be successful with the introduction of conservation measures it will be necessary to know if these measures fit within the farmer's perception and his/her social and financial possibilities. It was found that successfully applied conservation measures in the USA and northern Europe were hardly adopted by dryland farmers in developing countries mainly because of the biophysical limitations and poor socio-economic conditions.

To get insight in the reason(s) for the difference in adoption of conservation measures the following questions need to be answered: Why do farmers farm their land the way they do? This, for instance, will include: his/her main problems in farming, his/her perception of the wind erosion problem, land ownership, farm labor availability, crop choice and crop management. The answers to these questions should help to find the best fitted measures within the given context or the right incentives to implement better wind erosion control measures.

Wind Erosion Control

The negative impact of wind erosion on dryland cropping systems can be prevented by applying soil conservation measures. Wind erosion is most effectively controlled by reducing the wind velocity near the soil surface or by creating sufficient resistance of the surface to wind forces. Methods that have been extensively tested involve roughening of the soil surface, maintaining a protective soil cover, or using wind barriers (Tibke, 1988). For maximum effectiveness, a combination of control methods is desirable. While one method may provide better control during the growing season, another may be required when there is no crop in the field (Fryrear, 1993).

Soil roughening can be achieved by appropriate tillage operations that leave a sufficient quantity of non-erodible soil aggregates at the surface. The remaining loose, erodible particles may be moved during strong winds, but will be quickly trapped in the lee of the stable aggregates. Soil movement will stop, and erosion is controlled. The same can be achieved by creating ridges at the surface which are perpendicular to the prevailing erosive wind direction. Generally, the sandier a soil the more fragile the aggregates, and the less effective soil roughening will be. If tillage is used to control wind erosion the soil must be tilled again whenever the non-erodible aggregates or ridges are destroyed by rain (Fryrear, 1993).

Several measures exist to maintain sufficient soil cover for wind erosion control. Leaving post-harvest crop residue as a flat mulch on the soil surface is an easily applicable and widely applied technique. However, leaving the same quantity of residue standing at the soil surface is much more effective in reducing wind erosion (Siddoway *et al.*, 1965). The soil cover required depends on soil texture; a sandy soil is more erodible and therefore requires more effective soil cover than loam and clay soils. A slightly different technique is the use of cover crops. These are usually sown when residues appear inadequate to reduce erosion, or when wind speeds outside the cropping season are high (Tibke, 1988).

Wind barriers consist of trees or crops planted in a strip perpendicular to the prevailing erosive wind direction. They effectively reduce the wind speed downwind of the barrier. The reduction in speed depends on the porosity and the height of the barrier. For most design purposes, the protected zone is assumed to be ten times the height of the barrier, but the actual protected zone depends on the velocity of the approaching wind and the erodibility of the soil. The higher the wind velocity and the more erodible the soil, the smaller the protected zone (Fryrear, 1993). Optimum porosity of a wind barrier is around 50% (Manohar, 1970).

Many of the wind erosion control methods described here have been successfully applied in the USA and northern Europe. But the adoption of these measures by dryland farmers in developing countries has been much less, mainly because of poor socio-economic conditions and biophysical limitations. Roughening of the surface by tillage is not always possible as not all small-scale farmers possess tillage implements and a tractor or animal traction. In addition, in areas where the wind erosion problem is most severe, soils are usually sandy and thus the effect of tillage will be limited. Mulching with post-harvest crop residues, either standing or flat, is without doubt the most widely applied soil conservation measure in drylands. It not only prevents wind erosion, but also protects the soil from crust formation and water erosion. However, mulching is limited by the inadequate quantity available for soil conservation purposes. In general, biomass production in arid and semi-arid regions is low, and the residue is also needed for other purposes, like fuel, fodder and construction. Cover crops are often not practical because they compete for nutrients and soil moisture, which is also true for live wind barriers of trees and shrubs. Other problems with establishing effective wind barriers are the often irregular fields, the variable wind directions during the year, and management constraints like pruning and preventing tree felling. In summary, adequate wind erosion control in many arid and semi-arid drylands is currently not achieved due to poor socio-economic conditions, low biomass production, competition effects, and management constraints. Therefore, a need exists to explore alternative control techniques that better fit into dryland farming systems in developing countries.

Natural Vegetation

One aspect that has largely been neglected in wind erosion research is the soil protection created by natural vegetation of scattered trees and shrubs, which is the characteristic vegetation type in many arid and semi-arid drylands (Fig. 3). The technique is not really new. It has already been applied in several areas over the world, but received only little attention in the wind erosion literature thus far. In general, vegetation shelters the soil from the erosive force of the wind by covering a proportion of the surface; it also reduces the shearing force near the ground by extracting momentum from the wind, and it catches soil particles in transport, thereby

Fig. 3. Typical landscape in a dryland area: farm land with spots of natural vegetation

acting as a sediment trap (Fig. 4; Wolfe and Nickling, 1993).

So far, detailed quantitative knowledge of the impact of scattered vegetation on near-surface wind speeds at spatial scales ranging from the flow around an individual obstacle to the flow over a more or less homogeneous, but sparsely vegetated area is limited (Kainkwa and Stigter, 1994). Currently the main source of quantitative information is the scientific papers describing wind tunnel experiments with low densities of flow-disturbing obstacles (roughness elements). These studies are not easily translated to natural conditions for the following reasons: (i) the roughness elements investigated are usually of a more simple geometric nature as compared with vegetation, and (ii) the flow conditions in wind tunnels are more homogeneous and less turbulent than in the field. However, despite of the limited quantitative data, considerable qualitative evidence for the technique has been gathered over the last few decades. The rationale of the idea is simple: by introducing enough roughness elements to the landscape to be protected (for example, by planting large amounts of trees and shrubs along existing roads and field borders, implanting small groves all over the area, etc.), a large-scale surface roughness is created. Assuming a sufficient density of roughness elements the global wind profile in the atmospheric boundary layer will slightly lift, comparable to what happens during an aerodynamic zero plain displacement. The wind speed near the ground will thus diminish, reducing the risk of wind erosion.

Farmers from villages in Niger, West Africa, have already mentioned the potential role of natural vegetation in wind erosion

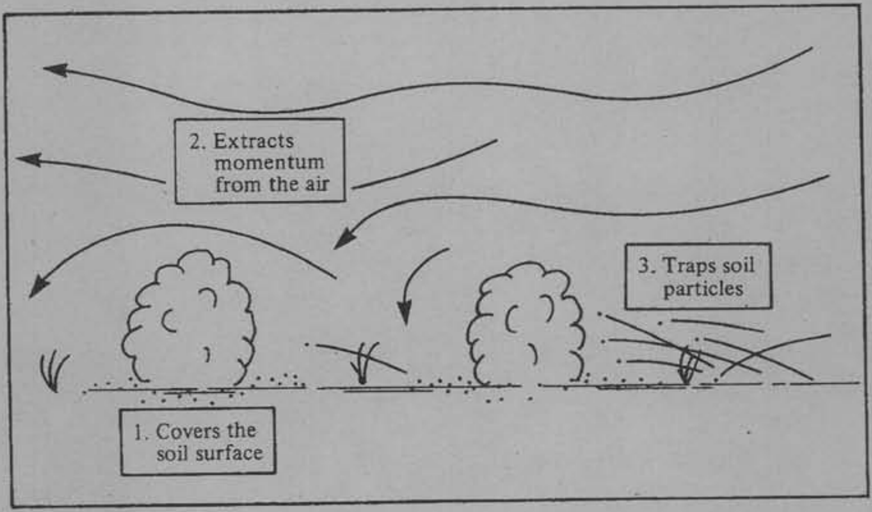

Fig. 4. The stabilizing role of vegetation (Wolfe and Nickling, 1993).

control (Sterk and Haigis, 1998). Unfortunately, in many dryland areas much of the original vegetation has been destroyed for construction material, fire wood, expansion of the cropped area, and by overgrazing. In an agricultural project in south-central Niger, natural woody vegetation was regenerated and incorporated into the farming systems. The developed strategy was successful in reducing wind erosion, but was largely based on time-consuming trial and error testing which lasted more than ten years (Rinaudo, 1996).

It is not yet fully clear how vegetation affects wind-blown particle transport. Also, it is only partly known how much vegetation cover is needed for adequate soil protection (Wolfe and Nickling, 1993). The latter is very much dependent on the spatial scale that is considered. At the scale of an arable field without any vegetation other than a crop, wind erosion may cause severe losses of soil particles, organic matter and nutrients. But a field with a dense vegetation cover, e.g., when under bush fallow, adequately protects the soil against erosion and can trap sediments eroded from unprotected fields. This means that when a scale larger than the field scale is considered, there may be enough protection to keep the mass balance between wind-eroded and wind-deposited materials close to zero at that scale.

Conclusions

Agricultural development in the world's drylands is severely constrained by soil degradation. Wind erosion is one of the main degradation processes in drylands. There is a good knowledge about the processes that take place and there are good techniques available to measure these processes in the field. The effects of wind erosion are well documented, but there is still little insight in the actual on- and off-site short- and long-term financial and economic effects of wind erosion in these dryland regions. A systematic approach for the assessment of wind erosion risk and actual costs can help to identify those regions where conservation measures benefit most.

Further research is also needed to find adequate wind erosion control methods. Present conservation techniques are currently not successfully applied in drylands in the arid and semi-arid countries. The main reasons for this are the poor socio-economic conditions like the lack of labor or capital, and biophysical constrains like a too low crop biomass production for sufficient quantities of mulch, or the measures introduce competition for water and nutrients with crops.

A potential solution for better wind erosion control in drylands is using the protective properties of scattered trees and shrubs. An agricultural development project in the Sahel has proven that it is possible to protect the soil from damaging winds by management of natural vegetation. But, basic knowledge of the effects of this vegetation on wind speed and sediment transport is limited, and detailed quantitative research on the impact of natural vegetation (shrubs and trees) on wind speed and soil erosion is needed. This research should result in models that are able to predict the effects of scattered vegetation on wind speed and soil erosion. These models could help develop wind erosion control strategies that fit into local farming systems, and make use of the locally occurring species of trees and shrubs.

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