Threats To Soil quality in Denmark

A review of existing knowledge in the context of the EU soil thematic strategy

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DISTURBING AGENTS (PRESSURES)

MANAGEMENT
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RISK AREAS
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SOIL SYSTEM (STATE AND IMPACT)
7. Soil erosion by water

7.1. Is water erosion occurring in Denmark?

In this section water erosion is understood to be a process of accelerated erosion due to man’s management of the soil resource, in contrast to the natural process of landscape formation. In Denmark spectacular soil erosion events are rare and erosion risk is generally perceived to be low due to a relatively low relief and low rainfall erosivity (e.g. Hansen, 1989; Van der Knijff et al., 2000; Veihe et al., 2003). Summarizing the few erosion studies, Veihe et al. (2003) gave a typical soil erosion rate of <3 t ha\(^{-1}\) yr\(^{-1}\) for Denmark. Erosion occurs on most soil types, typically in the autumn and winter after prolonged periods of rainfall, in connection with snowmelt and with rainfall on frozen soil.

In a systematic plot experiment, the effect of cropping and tillage on erosion was investigated at two sites in central Jutland, a loamy sand (Danish classification: JB4) and a sandy loam (JB6), over a period of three years (Schjønning et al., 1995). The plots had linear slopes of ca. 10\% and corresponded to USLE (Universal Soil Loss Equation) erosion plots. Annual erosion rates in winter wheat sown along the slope varied between 1.7 and 26 t ha\(^{-1}\) at the sandy site and 0.2 and 1.7 t ha\(^{-1}\) at the loamy site. The differences were explained by soil texture, soil structure and, to a lesser extent, somewhat different rainfall patterns. Lower erosion rates were measured in different plot experiments in western Jutland and eastern Denmark (Hasholt, 1990). However, in those experiments the slope gradients were either <4\% and the soils coarse sandy, or ploughed plots lay bare in winter, substantially reducing the erosion risk due to larger depression storage capacity (Hansen et al., 1999).

![Figure 7.1. Measured rill erosion rates in spring and autumn on 213 slope units in Denmark (Djurhuus et al., 2007).](image)

In an extensive field study, rill erosion was surveyed on 189 slopes units in different parts of Denmark in the autumn and spring between 1994 and 1999. Loamy sands and sandy loams
were the dominant soil types. In only 20% of the surveys could rill erosion be detected. The mean annual erosion rate on all slopes was 0.6 t ha\(^{-1}\). The non-zero erosion rates were highly right-skewed, with a median of 0.7 t ha\(^{-1}\) yr\(^{-1}\), a 75% quantile of 1.9 t ha\(^{-1}\) yr\(^{-1}\) and a maximum of 37 t ha\(^{-1}\) yr\(^{-1}\) (Fig. 7.1; Djurhus et al., 2007). Where erosion occurred, the distribution of rill erosion rates was broadly similar to those reported from other northern and western European field studies (e.g. Alström & Bergmann, 1990; Broadman, 1990; Govers, 1991; Chambers & Garwood, 2000).

In absence of a soil erosion model for Denmark, the relative erosion risk in the country was mapped with the spatially distributed soil erosion model WaTEM (Van Oost et al., 2000), which is based on the USLE (Renard et al., 1996). Accordingly, 10% of the agricultural land was vulnerable to soil erosion by water in 2003, assuming that winter wheat was grown on the whole area (Heckrath et al., unpublished data). Unlike the traditional USLE, WaTEM calculates the upslope contributing area of a given point instead of the slope length as part of the topographic factor (L) in the model (Desmet & Govers, 1996). Therefore WaTEM accounts more accurately for runoff patterns on complex topography. Both the erodibility (K) and the erosivity (R) factors of the USLE were adapted for Danish conditions.

7.2. What is the impact of water erosion to the soil and the environment?
Accelerated water erosion is both a threat to the soil resource and may cause pollution, especially eutrophication, of surface waters. In Denmark only the latter has been of concern and was the prime motivation for initiating erosion studies. The adverse effects of soil erosion on soil quality and agronomic productivity are well-documented in the literature (e.g. Lal, 2001; Govers et al., 2004). Similar to elsewhere, the most severe effects at eroding sites in Denmark comprise the loss of fine-textured material, organic matter, nutrients and available water capacity as well as a general decline in soil structure. Colluvial deposits on sites with sandy, weakly structured soils are often depleted in clay and organic matter. Although these processes impair soil productivity in the long term, it is difficult to quantify the productivity loss due to soil erosion, because of the confounding effects of climatic factors, landscape position and management. Measures other than soil productivity may need to be included to assess the potential threat to the soil.

To our knowledge, there are no specific reports on water erosion-induced soil degradation for Denmark. Likewise, a critical erosion rate, beyond which lasting damage of the soil occurs, has not been defined. Compared with the rate of soil development, which in temperate Denmark is substantially less than 1 mm yr\(^{-1}\), even small erosion events can impair the integrity of the soil pedon. On the basis of the extensive rill erosion survey, however, we conclude that water erosion in Denmark presently is a minor threat to the agronomic productivity of soils.

7.3. Identification of risk areas regarding water erosion
Models are commonly used for identifying areas vulnerable to erosion. Most of those combine expressions of erosivity and erodibility with topographic and crop management functions. In Denmark the USLE has been used as a qualitative indicator of erosion risk
(Olsen & Kristensen, 1998). However, as water erosion is a relatively infrequent and highly variable event under Danish conditions, the probability of erosion occurring ought to be explicitly considered in modelling. To this end, data from the rill erosion survey (see Section 7.1) were used to develop an expert system for predicting water erosion in Denmark (Djurhuus et al., 2007).

7.3.1. Water erosivity for Danish climatic conditions
Climatic or rainfall erosivity is a cause of regional variations in water erosion potential. In a recent study the magnitude and frequency of erosive rainfall was determined for Denmark for the period 1954 to 1996 (Leek & Olsen, 2000). To this end, an empirical submodel of the USLE, the rainfall erosivity index ‘R’, was calculated based on the rainfall energy and intensity. The model quantifies the net effect of the kinetic energy of the raindrops on impact with the soil, and the amount and rate of runoff likely to be associated with the rain.

Table 7.1. Average annual rainfall erosivity for four selected years at six weather stations in Denmark (Leek & Olsen, 2000).

<table>
<thead>
<tr>
<th>Year</th>
<th>1967</th>
<th>1990</th>
<th>1993</th>
<th>1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean erosivity, R, (MJ mm m^{-2} hr^{-1})</td>
<td>0.026</td>
<td>0.045</td>
<td>0.030</td>
<td>0.053</td>
</tr>
</tbody>
</table>

Figure 7.2. Annual distribution of monthly rainfall erosivity (R) for the linear least square trend 1954-96 for six weather stations. The dotted line represents 1954 and solid line 1996 data (adapted from Leek & Olsen, 2000).

There was a considerable but random regional variation of erosivity during the period (Leek and Olsen, 2000). That is, the geographic location of high erosivity will vary considerably from year to year. Table 7.1 shows average annual values from six weather stations for four years. Rainfall erosivity in Denmark was low compared with other parts of northern and western Europe, (Morgan, 1995, Chapter 4) and an order of magnitude lower than erosivity in the eastern half of the USA (Wischmeier & Smith, 1978). Erosive rainfall increased between
1954 and 1996 and so did erosivity, especially in the autumn (Fig. 7.2). This rising trend in annual precipitation in Denmark is expected to accelerate according to the latest projections of climate change (e.g. Jeppesen et al., 2009) and hence rainfall erosivity in autumn. This coincides with the time of the year when soils tend to be rather vulnerable to water erosion.

The newly-developed expert system for predicting water erosion consists of three parts: a logistic model predicting the probability of erosion, a model predicting a conditional erosion rate only in cases where erosion occurs, and a third model predicting the soil surface roughness. Surface roughness, in turn, is a variable in the probability model. The number of storms with >20 mm rainfall only had a minor effect on the probability of erosion. In contrast, the magnitude of erosion depended strongly on the annual amount of erosive rainfall. This underlines the importance of the climate change-induced rising rainfall erosivity for the erosion potential in Denmark.

Crop and soil management are decisive for the extent of water erosion. Plant cover and crop residues protect the soil from raindrop impact, while roots contribute to the mechanical strength of soils. In the long term, crop management affects soil structure and hence both soil strength and water infiltration, which, in turn, are important factors for water erosion (see Section 5.2). Tillage and seedbed preparation determine soil surface roughness and therefore depression storage capacity (Hansen et al., 1999). Ploughed land with its large capacity to store water delays runoff initiation. Contour tillage and planting is often reported to reduce soil loss under low rainfall intensity, as micro-topographic features reduce runoff velocity. Experimental evidence both from controlled plot experiments and the rill erosion survey stresses the vulnerability of winter cereals to water erosion in Denmark, especially when sown along the slope (Schjønning et al., 1995). In contrast, erosion was practically absent on fields with grass, catch crops or cereal stubble and intermediate for ploughed soil (Djurhuus et al., 2007).

7.3.2. The ability of Danish soils to withstand the mechanical stresses from surface water runoff

Erodibility describes a soil’s inherent resistance to erosion, i.e. both detachment and transport. Hence, erodibility is defined independently of other factors controlling water erosion like rainfall, topography and crop management. Erodibility varies with soil texture, soil structure, soil strength, and soil chemical composition. The least resistant particles to detachment and transport are silt and fine sand. Coarse sand requires greater forces for entrainment, while clay makes soils more cohesive and resistant to detachment. Accordingly, loamy sand and sandy loam soils prevalent in Denmark are typically moderately erodible (Renard et al., 1996). An erodibility field test on 11 representative Danish soils showed that clay was the single most important parameter explaining soil loss for a range of clay contents between 4 and 20% (Schjønning et al., 1995, Chapter 11). In this study, clay content also correlated positively with soil porosity, which in turn increased infiltration and reduced runoff. Similarly, both the probability and the magnitude of erosion declined in soils with increasing content of the combined clay and fine silt (2-20 µm) fraction in the Danish rill erosion survey. This could be
explained by higher aggregate stability and surface roughness with increasing clay and fine silt content, both of which reduce erodibility.

One of the most commonly used erodibility indices is the K factor of the USLE (Wischmeier & Smith, 1978), which describes soil loss on a standard erosion plot per unit of the erosivity factor R. From a large amount of American experimental data, a soil texture-based pedotransfer function for the K factor was developed that greatly facilitates erodibility estimates. However, although the K factor pedotransfer function is well established for agricultural soils in the USA, employing it for other parts of the world may be subject to error due to variations in soil properties. A weakness of the K factor, in general, is that it does not account for seasonal patterns in erodibility related to, for example, tillage-induced changes in bulk density and hydraulic conductivity or freeze-thaw cycles.

Despite these limitations, we calculated the K factor according to Renard et al. (1996) from data of the Danish Soil Database (http://www.djfgeodata.dk), because soil conditions in Denmark were considered sufficiently similar to those in the USA. The use of the K factor pedotransfer function thus permitted the mapping of erodibility in Denmark at 250 m-resolution and the comparison with published data. Organic lowland soils were excluded from the analysis. The K factors for agricultural land were broadly similar on the two main islands, Seeland and Funen (Table 7.2), which are dominated by sandy loams developed on glacial till. Geology and soils are somewhat more versatile in Jutland. Fine sands in the north, coarse sands on the outwash plain in the west and loamy soils on glacial till in the east result in a broader distribution of K factors in Jutland (Table 7.2). The K factor is commonly divided into erodibility classes where K factors below 25 and above 45 indicate low and high erodibility, respectively (Römkens, 1985). Thus, most agricultural soils in Denmark are classified as moderately erodible. Jutland also had a substantial proportion of soils with low erodibility and the only highly erodible soils in Denmark, Aeolian sands, were found in the north of Jutland and occupied about 3% of its agricultural land.

Table 7.2. Summary statistics of the K factor (kg hr MJ⁻¹ mm⁻¹) calculated for agricultural land in different parts of Denmark in 2003 excluding organic lowland soils (unpublished data).

<table>
<thead>
<tr>
<th></th>
<th>25th percentile</th>
<th>median</th>
<th>75th percentile</th>
<th>90th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jutland</td>
<td>20</td>
<td>28</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>Funen</td>
<td>30</td>
<td>33</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>Seeland</td>
<td>32</td>
<td>34</td>
<td>36</td>
<td>38</td>
</tr>
</tbody>
</table>

Topography often exerts a large control on water movement on the soil surface. The topographic effect is here understood as the system’s resistance to an external pressure, namely rainfall erosivity. Water erosion usually increases both with slope steepness and size of the upslope drainage area as a result of respective increases in velocity and volume of surface runoff. One of the most well-known attempts to describe this combined effect is in the form of the length-slope (LS) factor of the USLE (Wischmeier & Smith, 1978), which is linearly correlated with soil loss. To characterize the topographic effect on water erosion in Denmark, we used a modified, two-dimensional form of the LS factor. This modified LS
factor incorporated upslope drainage area rather than slope length and, therefore, better represented surface runoff on complex topography (Desmet & Govers, 1996). On the basis of a 10-m digital elevation model, LS factors were calculated for field blocks, with administrative units each comprising one or more agricultural fields and surrounded by permanent landscape features. This procedure set a natural limit for the size of the upslope drainage area. The average field block size was 11.6 ha. The distributions of LS values were broadly similar between the three major regions in Denmark (Table 7.2). In general, LS values were rather low, consistent with the countries’ mostly low relief. There are very few reports in the literature with which compare. In a Belgian catchment in the loess belt with widespread erosion problems, average LS values on moderately eroding sites were larger than the LS 90th percentiles in Denmark (Desmet & Govers, 1996). In some parts of Denmark, especially the eastern half of northern Jutland, eastern Jutland and western Funen, moderately high LS values >15 occurred on footslopes, comparable with observations from Belgium.

<table>
<thead>
<tr>
<th></th>
<th>median</th>
<th>75th percentile</th>
<th>90th percentile</th>
<th>99th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jutland</td>
<td>0.3</td>
<td>0.9</td>
<td>2.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Funen</td>
<td>0.4</td>
<td>1.1</td>
<td>2.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Sealand</td>
<td>0.3</td>
<td>0.9</td>
<td>2.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

In the Danish rill erosion survey, both the probability and the magnitude of erosion were found to increase with increasing LS values for the slope units. However, the effect was rather weak compared to other variables such as cropping system and presence of an impermeable layer in the root zone. By and large, topography had little influence on the soils’ vulnerability to water erosion in Denmark.

7.3.3. Relating climatic erosivity to the soil’s resistance to degradation

There is no simple spatial pattern of erosion events on sloping land in Denmark. Rainfall erosivity varies randomly between regions, erodibility is rather uniform and the relief is generally low. On the other hand, crop management and subsoil conditions have a strong influence on both the probability and the magnitude of water erosion (Djurhuus et al., 2007). Therefore, the assessment of erosion risk ought to be done at the field scale. Most erosion models predict erosion risk by relating expressions of erosivity to the soils’ ability to resist soil loss. This approach was also used for the development of the water erosion expert system in Denmark (Djurhuus et al., 2007), which makes it directly suitable for the purpose of identifying risk areas. Some important variables of the expert system have been described in the previous sections. Figure 7.3 shows as an example the effects of different variables on predictions of median erosion rates for selected scenarios representing typical variable combinations. For the first scenario (Fig. 7.3 a), the variability of the predicted erosion rates is also shown as quantiles (Fig. 7.3b).

The largest median erosion rate of up to 3 m³ ha⁻¹ (c. 4 t ha⁻¹) was predicted for winter cereals on a south-facing slope with an impermeable layer and 700 mm precipitation.
accumulated over days with >8 mm precipitation (Fig. 7.3 c). This scenario shows the relatively minor effect of aspect compared to the importance of impermeable layers. As impermeability often is the result of soil compaction (Chapter 5), this is an example of how one aspect of soil degradation amplifies another. Whereas topography had little influence on a soil’s vulnerability to water erosion (Fig. 7.3d), the effect of soil texture on erodibility was more marked, especially for small grains (Fig. 7.3a). The expert system also predicts the variability of water erosion risk for given variable combinations. The example in Figure 7.3b shows substantial tailing towards higher erosion risk. This information is particularly useful for identifying high-risk areas due to a larger differentiation of risk than the prediction of median erosion is able to.

![Graphs](image)

Figure 7.3. Predicted median erosion (m³ ha⁻¹) as a function of clay+silt (a), accumulated precipitation for days with precipitation > 8 mm (c) and LS-99% quantile (d). Also, (b), the mean and the 25, 50 and 97.5% quantiles from the distribution of predicted erosion rates for small grains (winter cereals) corresponding to (a). For the variables that are not explicitly listed in the figures the following settings were used: clay+silt: 30%; water impermeable layer: not present; aspect: north; precipitation and snowmelt on frozen soil: 12 mm (a) and 0 mm (c, d); days with precipitation > 20 mm: 2 (a) and 0 (c, d); accumulated precipitation for days with precipitation > 8 mm: 230 mm; LS-mean: 2.75 (a) and 1.5 (c); LS-99% quantile: 15 (a) and 7 (c) (unpublished data).

### 7.4. Decisions on risk reduction targets

The extent of soil degradation due to water erosion has been little investigated in Denmark and, to our knowledge, there has barely been a technical debate regarding tolerable levels of soil loss. As pointed out above, water erosion was only seen as a potential threat to the aquatic
environment. Lacking scientifically documented critical thresholds, we argue that the preservation of the long-term integrity of the soil resource ought to take precedence over a more short-term abatement strategy based on documented soil productivity loss. This is consistent with the precautionary principle manifest in the EU Soil Thematic Strategy. Therefore, water erosion ought to be prevented on agricultural land where it is likely to frequently cause rill erosion. The critical factor combinations are assessed by employing models like the rill erosion expert system. This categorical approach to risk reduction implies that the vulnerability to rill erosion is confirmed locally.

7.5. Programme of measures to reach risk reduction targets

Water erosion reduction measures are widely reported in literature (e.g. Morgan, 1995) and well tested. Principally, conservation strategies aim at increasing water infiltration to reduce runoff volumes and erosivity, strengthening topsoil resistance to detachment of soil particles and protecting the soil surface with plant or residue cover (e.g. Govers et al., 2004). Soil cover both enhances infiltration and reduces detachment. The same effects are achieved by maintaining an adequate soil organic matter (SOM) content and lime potential, which results in good soil structure, macroporosity and aggregate stability (Chapter 6). A well-developed root system furthers both soil cohesion and macroporosity and therefore affects infiltration and detachment. A rough soil surface has a large depression storage capacity for rainfall allowing more time for infiltration and dissipating runoff energy. Surface roughness is controlled by tillage practices. Wheel tracks typically have a low infiltration capacity and are important for runoff generation, which is why they should be removed mechanically.

Poulsen & Rubæk (2005) listed a number of suitable conservation options for Denmark, which practically eliminate the erosion risk. The simplest and most cost-effective are adapted crop and soil management to minimize erosion risk. On vulnerable areas, winter cereals ought to be omitted unless sown by direct drilling. Alternative options are catch crops or harrowed stubble during the runoff season. As a measure of landscape engineering, grassed waterways can be established across the steepest slopes breaking runoff connectivity.

7.6. Knowledge gaps and research needs

In Denmark research needs regarding water erosion mainly evolve in the context of protecting the aquatic environment. However, the following issues also are relevant in view of soil protection:

- Quantitative analysis of water erosion impact on long-term soil fertility and soil functions in different agro-landscapes.
- Assessment of climate change impact on water erosion risk including anticipated changes in cropping systems.
- Implementation and evaluation of the Danish expert system as a practical, web-based tool for erosion control and conservation planning.
8. Soil erosion by tillage

8.1. Is tillage erosion occurring in Denmark?

Whenever soil is cultivated, tillage moves very substantial amounts of soil in the cultivation layer. Spatial variations in the magnitude of soil movement during tillage along a hillslope cause net gain or loss of soil locally. This process is referred to as tillage erosion (Govers et al., 1999). Characteristically, tillage erosion removes soil at convexities such as crests and shoulder slopes and deposits it again at the concavities of footslopes and hollows. The linear slope sections remain stable. Hence tillage-induced soil redistribution primarily depends on the change in slope gradient in tillage direction. This means that the rate of tillage erosion often is described as a simple linear function of slope curvature (Govers et al., 1994). Field boundaries will act as a line of zero transport, so that soil loss will take place at upslope field boundaries, whereas accumulation occurs at downslope field borders, leading to the formation of soil banks. The spatial signature of tillage erosion differs fundamentally from that of water erosion: soil loss by tillage will be most intense on landscape positions where water erosion is minimal. Another important difference between water and tillage erosion is that the latter is solely a process of soil redistribution within fields. In contrast to often unreliable data on the extent of water erosion, tillage erosion estimates depending only on topography and tillage management are considered robust (Van Oost et al., 2006).

Given the nature of the process, tillage erosion must be assumed to be widespread on rolling topography in Denmark. However, only a few field surveys (Van Oost et al., 2003; Heckrath et al., 2005) and controlled tillage experiments (Heckrath et al., 2006) have been conducted in Denmark. This research was supported by findings from other countries and has fundamentally contributed to the development of tillage erosion and soil property evolution models (Van Oost et al., 2005; Van Oost et al., 2007). Systematic tillage experiments involving physical tracers showed tillage erosion rates between 10 and 20 t ha$^{-1}$, depending on tillage direction on typical slopes in central Jutland (Heckrath et al., 2006). In recent years the spatial patterns of the fallout radionuclide caesium-137 ($^{137}$Cs) have increasingly been analysed to trace soil redistribution on agricultural land over the last 40 to 50 years (Quine, 1999). This methodology was employed on a field with representative hummocky topography in northern Jutland. In summary, eroding sites averaged soil losses of 20 t ha$^{-1}$ yr$^{-1}$ due to tillage, whereas depositional sites received about 10 t ha$^{-1}$ yr$^{-1}$. One third of the field exhibited tillage erosion rates larger than 15 t ha$^{-1}$ yr$^{-1}$, while another third correspondingly had substantial rates of soil deposition. Areas with maximum tillage erosion had lost about 0.15 m of soil over a period of 45 years (Heckrath et al., 2005). These results were confirmed at another field site in eastern Jutland (Heckrath, unpublished data).

It is therefore concluded that tillage operations have caused severe soil redistribution on arable fields in Denmark during the past decades – and still do – and that tillage erosion rates are at least an order of magnitude higher than for water erosion.

8.2. What is the impact of tillage erosion to the soil and the environment?

Tillage erosion is today recognized as an important process of soil degradation affecting soil productivity (Lal, 2001) or landscape evolution (Quine et al., 1997). Close relationships
between tillage erosion and the spatial pattern of soil organic carbon (SOC), total soil N, P, soil depth, available water capacity and above-ground biomass have been reported from different parts of Europe (e.g. Kosmas et al., 2001; Quine & Zhang, 2002; Heckrath et al., 2005). These studies have provided evidence that tillage erosion operates like a conveyor belt, transporting soil and soil constituents from convexities to concavities. Tillage causes severe soil truncation and loss of plough layer soil on convexities. Subsequently, as ploughing depth is maintained, less fertile subsoil material is incorporated into the plough layer and eventually leads to its degradation. Accordingly, areas of lighter soil colour around convexities, commonly observed in Denmark, are evidence of tillage-induced SOC depletion. Conversely, soil accumulates in concavities through downslope translocation from the upslope landscape elements. These relatively small areas, therefore, develop deep A horizons due to perpetual burial of the former plough layer. Hence, soil movement by tillage erosion is a major contributor to within-field variability of soil properties (Quine & Zhang, 2002; Heckrath et al., 2005) and has an adverse impact on soil productivity (Schumacher et al., 1999).

The effect of tillage erosion on soil properties was comprehensively studied at the field site in northern Jutland (Heckrath et al., 2005). Soil organic carbon and phosphorus contents in soil profiles increased from the shoulder towards the slopes. The significance of tillage erosion for soil profile anisotropy at this site was illustrated by a comparison of averaged soil property values in different erosion classes (Table 8.1). Stable areas were represented by tillage erosion rates of ~5 to +5 t ha\(^{-1}\) yr\(^{-1}\). While SOC contents in the 0-0.25 m layer were 13% higher on aggrading compared to eroding areas, the difference was 38% in the 0.25-0.45 m layer. The ratio between SOC contents in the 0-0.25 m and the 0.25-0.45 m layer was higher on eroding compared to aggrading areas. Ignoring dynamic processes of SOC turnover, a first approximation of SOC redistribution due to tillage erosion between erosion classes was calculated based on the plough layer SOC concentrations and the soil redistribution rates. We obtained SOC changes of ~220 and 150 kg SOC ha\(^{-1}\) yr\(^{-1}\) on eroding and aggrading areas, respectively (Table 8.1).

These results suggest that tillage erosion has important implications for SOC storage at the field scale. Eroded SOC is deposited in a subsoil environment with assumed much longer turnover times (Gill & Burke, 2002). Additionally, denuded shoulderslope positions may bind extra atmospheric carbon (Liu et al., 2003). To further investigate SOC fluxes induced by soil redistribution at this site, C dynamics were incorporated in a spatially distributed model including both water- and tillage-induced soil redistribution (SPEROS-C; Van Oost et al., 2005). The SOC patterns predicted by SPEROS-C were in good agreement with field observations. The model results confirmed that in fields with gently rolling topography, tillage erosion and deposition exert a large influence on SOC redistribution and soil profile evolution at a timescale of a few decades. The formation of new SOC at eroding sites and the burial of eroded SOC below plough depth provided an important mechanism for C sequestration on sloping arable land in the order of 30–100 kg C ha\(^{-1}\) yr\(^{-1}\). These findings have been supported subsequently by results from a number of arable field studies in different parts of the world (Van Oost et al., 2007). Therefore, any attempt to manage agricultural land to maximize C sequestration must fully account for tillage erosion and the fate of eroded and
buried SOC across the landscape. Increasing variability of SOC contents in soils will directly affect soil properties such as soil structure and aggregate stability and, in turn, nutrient cycling water retention and erodibility by water (Chapter 7). With declining SOC contents in topsoils, clay is to a lesser degree associated with SOC and therefore more readily dispersed. This may give rise to a larger colloid mobilization and translocation in soil profiles (Dexter et al., 2008).

Like SOC, total P was another soil property that evidenced a spatial distribution that appeared to be strongly affected by tillage erosion. There was a lower rate of decline of total P in soil profiles on aggrading compared to eroding areas and therefore a larger P enrichment of the subsoil. The overall evidence also suggested that crop productivity was affected by tillage-induced soil redistribution (Table 8.1). However, tillage erosion effects on crop yield were confounded by topography-yield relationships, and the effects could not be clearly separated.

### Table 8.1. Arithmetic means of spatially interpolated (block-kriged) soil properties for eroding, aggrading or stable areas at a field site in northern Jutland. Changes in SOC and total P are the product of erosion rate and the concentration of the respective soil property (Heckrath et al., 2005).

<table>
<thead>
<tr>
<th>Property</th>
<th>Eroding areas 48%</th>
<th>Stable areas 20%</th>
<th>Aggrading areas 32%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil redistribution rate</td>
<td>t ha(^{-1})</td>
<td>-20.2</td>
<td>4.0</td>
</tr>
<tr>
<td>SOC (0.025) (^\dagger)</td>
<td>g kg(^{-1})</td>
<td>11.5</td>
<td>13.3</td>
</tr>
<tr>
<td>SOC (0.025)</td>
<td>t ha(^{-1})</td>
<td>38</td>
<td>43</td>
</tr>
<tr>
<td>SOC (0.25-0.45)</td>
<td>t ha(^{-1})</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td>Change SOC (0.025) (^\dagger)</td>
<td>kg ha(^{-1}) yr(^{-1})</td>
<td>-224</td>
<td>7</td>
</tr>
<tr>
<td>Total P (0.025)</td>
<td>mg kg(^{-1})</td>
<td>446</td>
<td>556</td>
</tr>
<tr>
<td>Total P (0.025)</td>
<td>kg ha(^{-1})</td>
<td>1480</td>
<td>1820</td>
</tr>
<tr>
<td>Total P (0.25-0.45)</td>
<td>kg ha(^{-1})</td>
<td>840</td>
<td>940</td>
</tr>
<tr>
<td>Change Total P (0.025) (^\dagger)</td>
<td>kg ha(^{-1}) yr(^{-1})</td>
<td>-8.6</td>
<td>0.4</td>
</tr>
<tr>
<td>(A_h)</td>
<td>m</td>
<td>0.26</td>
<td>0.31</td>
</tr>
<tr>
<td>Grain yield</td>
<td>t ha(^{-1})</td>
<td>6.1</td>
<td>6.8</td>
</tr>
</tbody>
</table>

\(^\dagger\) label indicates soil depth in metres; \(^\dagger\) soil redistribution rate times soil content.

### 8.3. Identification of risk areas regarding tillage erosion

Unlike water and wind erosion, the effects of which can often be easily identified in the landscape, the extent and severity of tillage erosion only become apparent after several decades of tillage through variations in soil properties and the development of tillage-related landforms like soil banks. This is why attention has focussed on wind and water erosion and why tillage erosion has only been sporadic investigated in the last 20 years.

The extent of tillage erosion has not yet been mapped for the arable land in Denmark. However, the modelling concepts, the technology and the data are available for simple risk assessment tools to be developed.
Figure 8.1. Factors affecting tillage erosion. The process of tillage erosion can be seen as a function of the erosivity of a given tillage operation (TE) and the erodibility of the cultivated landscape (LE). This simple general concept is the basis for the following discussion. Adapted from Lobb et al. (1999).

8.3.1. Which tillage operations induce downslope movement of soil?
Compared to other soil erosion processes, tillage erosivity arises solely from soil management. Tillage erosivity – the potential of a given tillage operation to erode soil within a landscape – depends on several physical and human factors (Fig. 8.1). These include the type and the size of the tillage implement and the operational conditions such as tillage speed and depth, as well as direction. The practical relevance of tillage erosivity is that it corresponds to the proportionality factor relating slope curvature to tillage erosion rates (Govers et al., 1994). The mouldboard plough is the primary tillage implement in Denmark and in general the most erosive. However, some types of chisel ploughs are only slightly less erosive when used at tillage depths similar to the mouldboard plough (Van Oost et al., 2006). Tillage erosivity for particular implements has been studied intensively in the 1990s by measuring the translocation of physical or chemical tracers in controlled experiments on various landscape positions. Tillage erosivity was shown to increase with tillage speed and depth (Van Muysen et al., 2002; Heckrath et al., 2006). Pooling the results from 34 published international studies with mouldboard ploughs, Van Oost et al. (2006) found that different erosivities were to a large degree explained by the variation in tillage depth and to a lesser degree by speed. For example, an increase in tillage depth from 0.2 to 0.3 m resulted in a 150% rise in erosivity. Tillage direction also exerts an important influence on mouldboard erosivity on rolling topography. Heckrath et al. (2006) concluded from controlled tillage experiments in Denmark that erosivity increased in the order contour tillage, slantwise tillage turning the soil upslope, and up- and downslope tillage.
8.3.2. Which topographies are critical

Landscape erodibility is the propensity of a landscape to be eroded by tillage and depends on topography, physical properties of the soil as well as field size and shape (Fig. 10.1). The latter affect the generation of soil banks. The static variable topography exerts the dominant effect on landscape erodibility by tillage and hence its resistance to displacement. Soil translocation during tillage is a gravity-driven process, where translocation rates depend on the slope gradient. The rates are highest on steep slopes tilling in downslope direction and vice versa. With changing slope gradient in tillage direction, the masses of soil transported from and to a given point differ, causing either net soil loss or gain at this point (Govers et al., 1994). Therefore, the variation of slope curvature determines the magnitude of tillage erosion. A fragmentation of such topography into small fields increases the risk as soil banks become more abundant. The potential for tillage erosion has not been mapped for Denmark and the precise area of arable land affected by tillage and hence, on the majority of arable land in Denmark.

In Danish tillage experiments, tillage erosivity declined with increasing bulk density as the soil became more compact and by extension more cohesive. The effect was smaller than that of tillage speed, and for a rise in bulk density from 1300 kg to 1700 kg m\(^{-3}\) erosivity declined by 20% (Heckrath et al., 2006). However, following primary tillage, loose soil was shown to be much more vulnerable to tillage erosion than compact soil (Van Muysen et al., 1999).

8.3.3. Critical combinations of tillage operations and topography

Tillage erosion is ubiquitous on rolling topography in Denmark. The more undulating the landscape, the larger is the vulnerability to tillage erosion. Mouldboard ploughing parallel or in a steep angle to the aspect is the most erosive tillage operation. Therefore, the most erosive tillage operation also is the most common. Tillage erosion is exacerbated by variable tillage speed and depth, especially when downslope tillage is faster and deeper than upslope tillage. As tillage erosivity essentially only depends on the tillage operator, the variation of erosivity has a large random component. This introduces a degree of uncertainty regarding the predictability of tillage erosion. On the other hand, the operator’s control over erosivity also provides him with control over the magnitude of tillage erosion and suggests simple mitigation options. Field borders across a hillslope give rise to the formation of soil banks. Therefore, the partition of long slopes into separate fields increases the potential for tillage erosion.

As with water erosion, thresholds for critical soil truncation or soil burial have not yet been defined. Hence, we are currently unable to determine a tolerable range of tillage erosion rates. To show the effect of different operational conditions on tillage erosion rates we used a simple model (Van Oost et al., 2006) to calculate scenarios for mouldboard tillage parallel to the aspect on two convexities with constant curvature (Fig. 8.2). The large curvature implied a change in slope gradient from 11.3 to 5.7 degrees over a distance of 12.5 m, while the distance was 50 m for low curvature. Both curvature values are typical for rolling topography in Denmark; the lower value is more common. Even on the minor convexity, tillage erosion
rates reached 5 t ha\(^{-1}\) for the typical ploughing depth and speed of respectively 0.25 m and 5 km h\(^{-1}\) (Fig. 8.2). These erosion rates were high compared to water erosion rates in Denmark (see 9.1). Only by reducing tillage depth to 0.15 m and speed to 3 km h\(^{-1}\) did tillage erosion rates remain at about 1 t ha\(^{-1}\). Under the same low erosivity conditions, tillage erosion rates were about 5 t ha\(^{-1}\) for the large curvature.

![Graph showing tillage erosion rates](image)

Figure 8.2. Predicted tillage erosion rates for mouldboard ploughing as a function of tillage depth, speed and topography. The tillage direction is parallel to the aspect and the soil bulk density 1400 kg m\(^{-3}\). Based on Van Oost et al. (2006).

### 8.4. Decisions on risk reduction targets

Since both tillage-induced soil loss and soil accumulation within fields are much more severe and widespread than for water erosion, tillage erosion must be considered a substantial long-term threat to soil productivity in Denmark. Measured data and model scenarios from Denmark and other parts of northern Europe with similar topography and tillage intensity provide clear evidence that tillage erosion rates frequently exceed 20 t ha\(^{-1}\) yr\(^{-1}\) on eroding sites within fields. Next to land levelling, tillage erosion is the most severe process of human-induced soil redistribution in Denmark. In other words, tillage in its current intensity is 10 to 100 times as erosive as water erosion and it is much more widespread. Hence, it is incontrovertible that tillage erosion will inflict substantial cost on the agricultural sector due to loss of productivity on eroded sites or the implementation of fertility–enhancing measures in the long term. Consequently, we stress that concerted efforts should be made to minimize tillage erosion.

Despite the potential threat, surprisingly few have tried to quantify the impact of tillage erosion on soil productivity and other soil functions in agro-landscapes. One specific problem is that the effects of erosion and topography on crop yields are confounded. There is extensive evidence that different soil quality parameters are impaired (see 8.2), especially on eroding...
sites. However, a framework is lacking for holistically assessing the long-term impact on such central aspects as soil fertility and productivity, SOC storage and nutrient cycling and losses in a landscape context.

Defining risk reduction targets also requires consideration of the practicalities and costs of mitigation strategies and their monitoring. Intensive tillage and mouldboard ploughing is an integral part of modern Danish agriculture. Changing cultivation systems drastically may reduce crop productivity, affect land use and will inflict costs on the economy in general. Hence, the definition of reduction targets requires a comprehensive cost-benefit analysis of sustainable tillage in a given landscape. Therefore, we cannot set a qualified reduction target for tillage erosion at present.

Policymakers generally have two options for managing risk reduction targets. The first option leaves the reduction target unspecified and seeks to reduce tillage erosion through concerted and comprehensive national information campaigns and volunteer measures backed by incentives. The second option defines a mandatory upper limit of tolerable annual tillage erosion rates on eroding sites.

8.5. Programme of measures to reach risk reduction targets
Reducing tillage erosion in Denmark calls for regulatory measures and an administrative framework for implementing and assessing mitigation strategies over a longer period of time. To identify and map risk areas, model tools have to be employed that assess tillage erosion for different tillage operations in certain cropping scenarios. Irrespective of the choice between volunteer and mandatory measures, the mitigation options listed below apply. Characteristic for these options is that they all represent adapted tillage practices and take immediate effect. Some measures are simply good agricultural practice.

- The most effective measure is to convert from conventional to reduced tillage systems; with no-till, tillage erosion is eliminated.
- Reducing tillage speed and especially tillage depth substantially reduces tillage erosivity of conventional implements. Care should be taken not to increase speed for downslope operations.
- After contour tillage, slantwise tillage, turning the soil upslope, is the least erosive.
- The frequency of tillage operations should be reduced and the loosening of soil before mouldboard ploughing avoided.
- Long slopes should not be partitioned into separate fields to avoid the formation of soil banks.

8.6. Knowledge gaps and research needs
In Denmark the following major research needs follow from the discussions above:

- Holistic and quantitative analysis of tillage erosion impact on long-term soil fertility and productivity, SOC storage and nutrient cycling and losses at the landscape scale. This is a prerequisite for defining risk reduction targets.
- Comprehensive cost-benefit analyses of sustainable tillage and cropping systems in Denmark.
• Development of a practical, interactive tool for predicting and mapping tillage erosion for different tillage scenarios at the field scale. The web-based tool would serve educational and planning purposes mainly for land-users and advisors.