Sediment delivery to streams from adjacent slopes on agricultural land in Denmark

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Abstract A number of "slope units" (i.e. areas of field size or less, homogeneous in terms of runoff conditions, crop and tillage), have been selected for study in Denmark. The slope units are situated along water courses, lakes and wetlands in order to elucidate the transfer of sediment to the aquatic environment. This transfer is often related to the formation and development of rills. To study the physical factors and human impacts that influence the incidence of rilling, the slope units have been deliberately chosen from areas with an expected erosion risk. The results demonstrate that substantial amounts of sediment, up to 3600 t km^{-2}, can be delivered to the aquatic environment from adjacent slopes. The results confirm that long steep smooth slopes are especially prone to erosion. These physical factors are in Denmark partly influenced by land management and tillage. It is also demonstrated that the common practice of using winter sown crops to inhibit nitrate loss, can cause an increased delivery of sediment and associated nutrients. The related smoothing of the seedbed and the common practice of tillage up and down the slopes also increase the sediment delivery. It is confirmed that rilling is partly a response to human impact.

INTRODUCTION AND AIMS

Denmark, with an area of 43 000 km^2, is located in the temperate climatic zone (Køppen Cfb). The landscape is of glacial and fluvioglacial origin. The relief is low to moderate. The maximum altitude above sea level is only 172 m, but steep slopes (5-10%) are present, predominantly along valleys, terminal moraines and coastal cliffs in landscapes developed during the Weichsel glaciation.

Considering the above, it is to be expected that erosion rates should be low to moderate in a global perspective. On the other hand, Denmark has been cultivated intensively and 90% of the cultivated area is arable, i.e. tilled regularly. Today 67% of the area is cultivated. Recent changes in land use include extensive cultivation of winter sown crops (the green fields strategy to reduce the loss of nitrate to groundwater), afforestation, buffer strips and EC set aside policy. Attention has been given to soil erosion not because of concern for loss of soil fertility, but rather because of eutrophication problems occurring in lakes and coastal waters. A substantial proportion of the nutrients causing eutrophication originate from the cultivated area. Within the last 10 years several workers have demonstrated that significant rates of soil erosion can occur from fields in temperate Northern Europe and Scandinavia e.g. Morgan (1986), Uhlen (1986), Ahlstrøm & Bergman (1991) and Hasholt *et al.* (1990). Some of those cited above e.g. Ahlstrøm & Bergman (1991) and Hasholt (1991) pay special attention to the linkage between erosion on fields and the delivery of the eroded material to the aquatic environment and demonstrate that rill erosion is likely to be of special importance to rapid delivery of large amounts of sediment and associated nutrients, including phosphorus (Hasholt, 1991; Hasholt & Hansen, 1995). There is, however, insufficient understanding of this linkage and of the human impact to take appropriate steps to reduce sediment delivery. There is also a lack of knowledge as to the extent to which conservation measures are needed. Therefore a subprogramme within the Danish Strategic Environmental Programme has addressed erosion problems from the point of view of the relationship between sloping fields, rills and adjoining water courses and wetlands.

The following aims were identified for the subprogramme

(a) To obtain quantitative information concerning rates of erosion on slopes and the delivery of eroded material to the aquatic environment.
(b) To obtain quantitative and qualitative information concerning the importance of human impact on erosion processes due to land management.
(c) To study the significance of rills to erosion and sediment delivery, and the factors that influence the formation and development of rills under Danish conditions.

The project is carried out as a joint venture between the Institute of Geography (IG) and The Danish Institute of Plant and Soil Science (DIPS), this paper is based mainly on the part of the work carried out by the Institute of Geography.

METHODOLOGY

Selection of study areas

Earlier erosion research in Denmark (Hasholt *et al.*, 1990, focused on an areally representative sample of study sites, in order to extrapolate the findings to the whole country. This approach had the consequence that effort was expended on some areas with no erosion. In the present context, where the focus is on the cause and effect of erosion phenomena, it is believed more cost effective to concentrate on areas where the probability of erosion is high. The generalization of the results of the investigation should, however, be facilitated by the inclusion of all major types of landscape in the selection of investigation sites. High erosion probability (risk) and representative landscape types have been primary criteria for the selection of sites. Information on erosion risk and risk related to water courses in Denmark has been presented by Hasholt *et al.* (1989) and Hasholt *et al.* (1990). The identification of risk areas was based on slope steepness, erodibility (Wischmeier *K*-factor) and distance from the water course measured along the profile.

Based on the above, study sites were tentatively selected using topographic and geomorphological maps. Three areas were included because they were part of ongoing erosion research programmes. Because of the dynamic nature of land management and cultivation the areas chosen were inspected to confirm that they were risk areas during the period of the investigation and had not been taken out of crop rotation by, for example, afforestation. Permission to gain access also had to be sought from the owners. The ten areas selected were subdivided into smaller areas termed "slope units". A "slope unit" is a small independent source area with regard to surface runoff. It is the size of a field or less, cropped and tilled uniformly and separated from other units by permanent barriers, e.g. roads, ditches, and water divides and/or by temporary barriers such as dead furrows and crops. The location of the areas is shown on Fig. 1.

The investigation period

The investigation extended over three consecutive "erosion years", 1993/1994, 1994/1995 and 1995/1996. Earlier investigations, Hasholt *et al.* (1990) have shown that in Denmark erosion takes place mainly from the end of August, when rainstorms can fall on newly tilled soils, and throughout autumn and winter, when surface runoff can be caused by either rainfall and/or snowmelt. Erosion is very rare between mid-April and August, because the fields are covered by crops. In order to separate the mainly rainfall-induced erosion occurring during autumn, and the possibly more snowmelt-induced winter erosion, two field campaigns were carried out each year. The first was carried out in December after tillage and sowing of the fields with winter cereals. The second was carried out from late February to early April. The timing of the latter depended on weather and soils and the aim was to ensure that a maximum of factors responsible for erosion had had time to impact, in particular snowmelt. On the other hand the field investigations had to be carried out before spring tillage eradicated the results of erosion, such as rills and alluvial fans. Difficulties with respect to timing resulted in the exclusion of a few slope units because of early tillage.

The fieldwork

The following description refers to the part of fieldwork carried out under the auspices of the IG. A description of the fieldwork carried out by DIPS and the methodology used to collect soil physical data can be found in Schjønning *et al.* (1995)

Realizing that, because of tillage, soil erosion and its results in Denmark are not permanently present in space and time, it is necessary to be on the spot at the right place and at the right time. The strategy must therefore recognise the fact that the object of study is a "moving target". Due to the limited occurrence in time of the object of study, the time available for observation is limited. Therefore a skilled observer should be used and the programme should not last too long, in order to secure "synchronous" and therefore comparable observations.

The programme was designed to benefit from skilled observers by combining qualitative and semiquantitative visual observations with a few quantitative measurements of erosion. The skilled observers were students with a background in

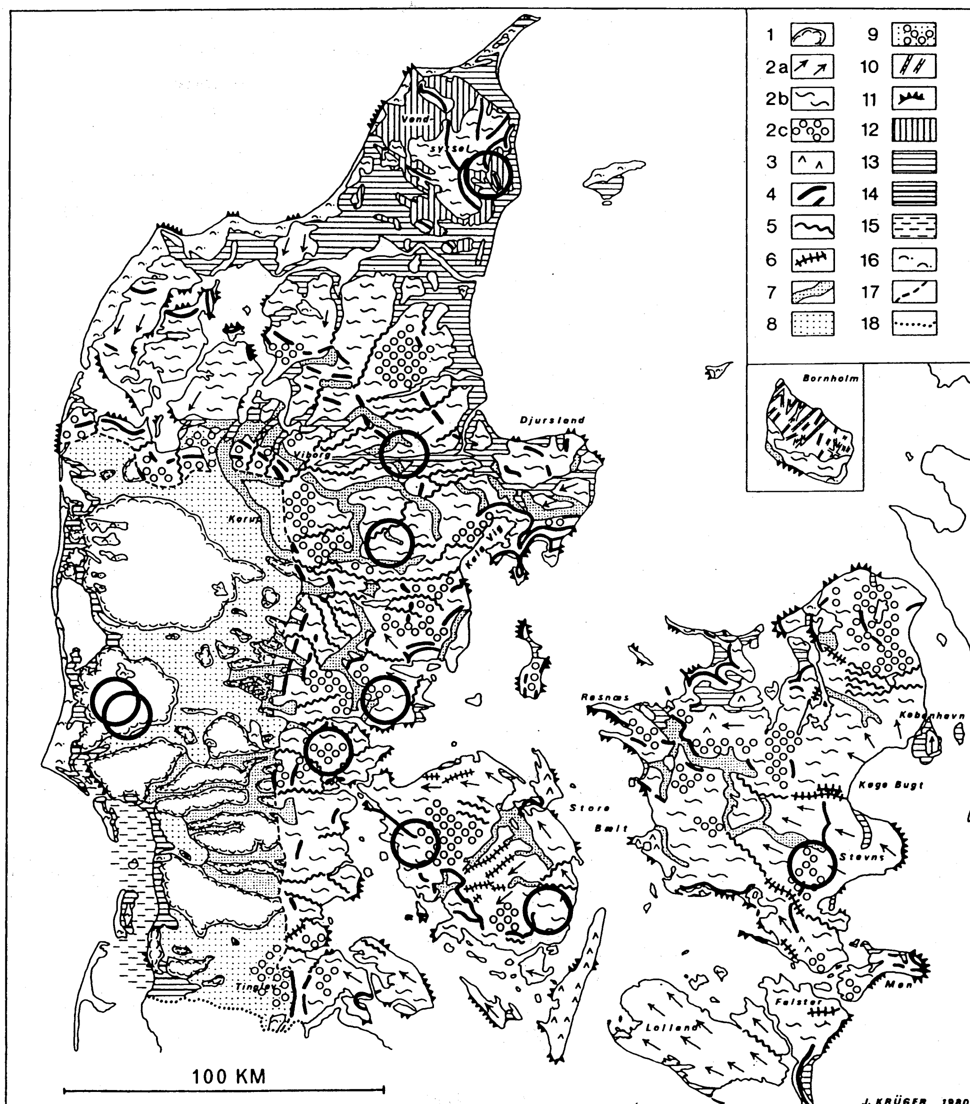

Fig. 1 A geomorphological map of Denmark. Circles indicate investigated areas.

1 = Morainic landscape from the Saalian glaciation, 2 = Morainic landscape from the Weichselian glaciation, a = Drumlinized ground moraine, mainly till plains, b = Undulating ground moraine, c = Hummocky moraine or fields of kames, 3 = Field of dislocated kames, so-called "hat-shaped" hills. 4 = Distinct ice-marginal hills. 5 = Tunnel valley, 6 = Esker, 7 = Extramarginal melt water valley or small outwash plain, 8 = Extensive outwash plain, 9 = Outwash plain with kettle holes, 10 = Fissure-valley landscape, 11 = High cliff, 12 = Marine foreland of Late-glacial age (the Yoldia plateau), 13 = Marine foreland built up since the Stone Age, 14 = Salt marsh, 15 = Tidal flat, 16 = Dune landscape, 17 = Main Stationary Line, 18 = The German border.

Compilation based on maps by Geological Survey of Denmark, Axel Schou, Per Smed & Johannes Krüger.

geomorphology and physical geography. The two member teams went through a common short course based on a field guide, Hasholt (1993). The field guide contained guidelines for documentation of:

(a) Information about the slope unit e.g. crop, tillage, roughness, tillage direction, slope etc.
(b) Erosion and sedimentation features e.g. evidence of overland flow, sheet erosion, rill and gully erosion, ponding, alluvial fans etc.
(c) The adjacent water course or wetland e.g. width of buffer strip, passage of water, vegetation, bank erosion etc.

The different slope units were surveyed on foot and the visual information was recorded in field notebooks using a standardized coding scheme, to speed up its collection. Supplementary documentation in the form of photos and videorecordings were also obtained. Where significant rill erosion and/or sedimentation was observed, the slope unit was surveyed by use of rulers, tape measures and calibrated pacing. Unmeasurable diffuse erosion patterns e.g. sheet erosion were recorded semiquantitively e.g. as strong, medium and weak. In the case of extensive rilling, representative rills were surveyed and the numbers of rills were counted. This procedure necessarily involves subjective elements and depends on the skill of the observer. Replication tests and control visits have, however, proved that the results are consistent and reproduceable.

RESULTS

Raw data exist in the form of maps, photos, video recordings and coded recordings and survey data in field notebooks. The different data were recorded and checked for obvious errors. For each campaign, the field books were decoded and compiled into tables. The rill eroded volume was computed from the surveys of rills for each slope unit, the downslope volume of accumulated sediment was also computed from survey results. The difference between the two is defined as the net erosion or the amount of sediment that passes from the slope unit into the water course.

The volumes of sediment were divided by the area of the unit to obtain an areal value, m^3 ha^{-1}. Table 1 shows for each "erosion year" the amount of rill erosion, sedimentation and delivery to the watercourse. The amount is expressed as a percentage of the observations of rill erosion within classes of m^3 ha^{-1}, e.g. in the "year" 1993/1994, 11% of 45 observations of rill erosion were in the class 2.5-4.99 m^3 ha^{-1}. There are significant differences between the single "years", in that 1993/1994 clearly has more erosion than the others. However 1994/1995 has one unit with very extensive rill erosion, whereas 1995/1996 has only low values. This mirrors the effect of climate e.g. the large scale erosivity of seasonal rainfall and snow cover and the small scale erosivity of single showers with limited areal coverage.

The computation was also carried out for the whole investigation period. It is clearly evident that low values dominate, although large values of rill erosion have occurred. Assuming a bulk density of 1.5 t m^{-3}, a maximum of 24 m^3 ha^{-1} equals 3600 t km^{-2}. Although the percentage of the rill erosion that was delivered to the water course varied from net sedimentation (shown in brackets in the Table) to

Table 1 Rill occurrence during the observation period.

No. observations of rill erosion	Year	Type	% of observations in class ($m^3 ha^{-1}$): 0-2.49	2.5-4.99	5.0-9.99	10-14.9	15-19.0	20-24.9	>25
45	1993/94	RE	58	11	20	7	2	2	0
		SE	78	9	13	0	0	0	0
	(3)	DI	69	13	11	2	2	0	0
25	1994/95	RE	80	16	0	0	0	4	0
		SE	88	12	0	0	0	0	0
	(28)	DI	64	4	0	0	0	4	0
21	1995/96	RE	90	10	0	0	0	0	0
		SE	95	0	5	0	0	0	0
	(19)	DI	81	0	0	0	0	0	0
91	1993/96	RE	71	12	10	3	1	2	0
		SE	84	8	8	0	0	0	0
	(13)	DI	70	8	5	1	1	1	0

RE = rill erosion, SE = sedimentation and DI = RE - SE

(.) Net sedimentation

100%, the median percentage for the years varied from 30% to 60%. However one slope unit with large rills showed no sedimentation, therefore approximately 3600 t km^{-2} was delivered to the stream.

In Table 2 selected attributes of the slope units are compared with equivalent information about the occurrence of rills. For each variable (e.g. crop or roughness index) a percentage of the total number of observations in a particular category is calculated. For each category, the percentage of rill occurrence is computed, as a percentage of the number of observations of that variable. Finally, the rill occurrence for a given type is given as percentage of the total number of rills for a given category. The relationship between rill occurrence for a certain category and the occurrence of this particular category provides an indication of whether rills are over- or under-represented. A value larger than one indicates over-representation, while a value between one and zero indicates under-representation. Unless there is a clear trend, values close to 1 should not be interpreted too rigidly.

Crop Fields with winter cereals have a large occurrence of rills (69%) and there is a clear over-representation (1.6). Surprisingly, fields without vegetation have only 16% rills which is an under-representation (0.6).

Tillage Ploughed fields have a low occurrence and under-representation while harrowed and sown fields show higher occurrence and over-representation. Fallow, stubble and no tillage show low values.

Roughness The maximum height difference (cm) within a "typical" area is used as an indication. Rills are clearly associated with low values. There is a trend toward stronger under-representation with increasing roughness.

Table 2 Factors influencing rill occurrence.

	% of obs.	% of rill obs.	% rill of obs.	Column 2 divided by column 1
Crop				
Winter cereal	42.8	69.2	37.8	1.6
Rape	2.0	1.2	14.3	0.6
Grass	19.1	4.9	6.1	0.3
No vegetation	26.0	16.0	14.4	0.6
Stubble/fallow	10.1	8.6	20.0	0.9
Tillage				
Ploughed	26.0	15.7	16.0	0.6
Harrowed	26.1	40.2	41.0	1.5
Sown	31.5	42.2	35.5	1.3
Fallow	13.8	2.0	3.8	0.1
Stub./no till	2.6	0.0	0.0	0.0
Roughness				
0-5 cm	39.7	41.7	26.7	1.1
5-10 cm	37.9	46.4	31.2	1.2
10-15 cm	12.4	8.3	17.1	0.7
15-25 cm	8.8	3.5	10.3	0.4
>25 cm	1.2	0.0	0.0	0.0
Slope length				
<50 m	7.2	1.2	4.5	0.2
51-100 m	30.9	44.2	38.8	1.4
101-300 m	40.3	33.7	22.7	0.8
>300 m	21.1	20.9	26.9	1.0
Slope				
0-3 %	16.0	2.4	3.9	0.2
3-9 %	57.9	60.0	27.2	1.0
9-12 %	21.7	30.1	36.2	1.4
>12%	4.4	7.2	42.9	1.6
Linear elements				
Dead furrows	29.0	30.2	32.7	1.0
Turn strip	37.0	38.5	32.9	1.0
Tracks	25.7	27.9	50.0	1.1
Water from field				
Even	67.2	59.8	29.5	0.9
Breakthrough	6.1	9.2	50.0	1.5
Ditch	0.4	0.0	0.0	0.0
Pipe drain	11.8	12.6	35.5	1.1
Ponding	5.3	11.5	71.4	2.2
Other	9.2	6.9	25.0	0.8
Buffer strip				
<1 m	17.5	22.4	34.0	1.3
<2 m	21.1	23.7	30.0	1.1
<5 m	22.1	23.7	28.6	1.1
<10 m	6.3	2.6	11.1	0.4
>10 and other	33.0	27.6	22.3	0.8
Deposition				
Pools	13.5	11.0	66.7	0.8
Stripes	24.3	21.5	72.2	0.9
Mini cones	22.1	24.9	91.8	1.1
Single cones	18.0	21.5	97.5	1.2
Composite cones	19.8	18.2	75.0	0.9
Other	2.3	2.8	100.0	1.2
Rill occurrence				
In tracks	30.0			
Concave slope	19.3			
Plane slope	13.3			
Convex slope	13.3			
Whole slope	24.0			

Slope length Rills occur frequently on slopes with a length of more than 50 m. Over-representation is found for lengths of 51-100 m.

Slope Rills occur frequently on steeper slopes, there is a clear trend in the over-representation values.

Width of buffer zone It is seen that rilling occurs frequently where the distance to the water course is very short. In general, the distances were short, and in 39% of the observations they were less than the 2 m required by law.

Water from the field Most often water running to the water course is evenly distributed. There is an over-representation of rills associated with breakthroughs and ponding near the water course.

Deposition It is clearly demonstrated that rills are associated with deposition in the lower areas of fields.

Rills The occurrence of rills in different places is given as a percentage of total occurrences. It is seen that fields with many rills account for 25% of the observations. Rills are frequent in tracks and are most often found on concave slopes. The relative occurrence of rill formation through time and space has also been investigated. Table 3 show the percentage of observations with rills found in the two annual campaigns. The autumn campaigns all have a lower percentage of rill formation than the spring campaigns. This demonstrates the effect of the moister conditions during the winter, together with the effect of snow. For the three year period 1993/1996, 23% of the observed areas had rills all three years, 29% had rills in two years, 41% had rills in one year and only 7% had no rills at all. In other words, these preliminarily identified "risk" areas have a 93% probability of rill occurrence within a three year period. The areas (slope units) with rill formation in all three years were examined for common features. It was an interesting feature that areas with frequent rill formation were mainly situated in young morainic landscapes from the Weichselian glaciation and in the marine foreland of Late glacial age(the Yoldia plateau). In 90% of the cases the crop was winter cereal, the rest were unvegetated. Tillage was mainly harrowed or sown. Roughness was less than 10 cm in all cases. The slope length varied, but with a tendency towards longer slopes. Slope was between 3 and 12%. Rill formation was very often found in dead furrows and on turning areas and tracks. Very often more than 30% of the slope unit was affected by rill formation and substantial sedimentation was found. The distance to water courses varied but shorter distances dominated, indicating that material eroded by rill formation will readily enter the water courses.

Table 3 Rill occurrence during the observation period.

	Late 1993	Early 1994	Late 1994	Early 1995	Late 1995	Early 1996
% of observations with rills	34	62	15	51	11	38

DISCUSSION AND CONCLUSIONS

An important question is, how accurate are the results? Experience from plot studies indicates that rill volumes can be measured within ±10% and this is confirmed for larger rills by Madsen (1992). Accumulation is more difficult to measure accurately, and the estimated accuracy is *ca.* ±20%. The accuracy depends on the size and the degree of preservation of the cross sections of the rill. Also the skill of the observer is very important, especially in cases with many rills, where "representative" rills are selected and multiplied by the total number of rills counted. The accuracies stated above are probably the best obtainable. In cases with small diffuse rills, the accuracy might be ± 100%, while larger rills will be measured more accurately. The accuracy is therefore variable, but not systematically biased. The evidence from single observations should therefore not be overemphasized, but an increased number of observations will tend to even out errors caused by inaccurate measurements. Estimation of variables, e.g. roughness, will show a different accuracy depending on the definition of the variable and how easy it is to measure or estimate. The observations of the occurrence of rills or a certain crop are quite reliable, once the observer has learnt to identify the object.

Another problem is that the number of slope units varies slightly through the investigation period. This is because new areas are included and a few are removed or simply not surveyed because of lack of time. In other cases, a large field can be split into several minor units because of crop rotation, and the reverse can also take place. Therefore frequency computations are based on the number of common slope units, and again the evidence from single observations should be handled carefully.

The direction of tillage, expressed as a compass bearing, was also investigated. The information from this attribute is, however, not clear and has therefore been omitted. Aspect would perhaps have been a better index. From the field maps it is seen that slope units are most often tilled in the direction of the long axis and very often up and down the slope.

It should be recognized that the results presented are representative only of areas with an expected erosion risk. Such areas cover a minor part of the total area of Denmark, amounting according to Hasholt *et al.* (1990) to about 3%. The proportion of risk areas situated near water courses has, however, not been investigated. The results from this investigation indicate that risk areas near water courses can contribute significantly to the transport of sediment in the water courses.

It is clearly demonstrated that the occurrence and further development of rills is multicausal. The effect of climatic differences in erosivity is seen in the contrasts in rill formation in the different years and seasons. The significance of differences in erodibility and landscape is seen from the frequent occurrence of rills in young morainic landscapes and in the Yoldia plateau. Human impact is clearly demonstrated through the variations caused by choice of crop and tillage procedure. It is seen that in areas with a high erosion risk caused by the natural conditions, inappropriate land management can cause high erosion rates. It is clearly demonstrated that the formation of rills can cause transport of large amounts of sediment to the water courses. Many of these findings confirm earlier results. However, this investigation is the most comprehensive of its kind undertaken to date in Denmark and it strengthens the conclusions of previous work.

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