Soil erosion and sediment delivery through buffer zones in Danish slope units

BRIAN KRONVANG, ANKER R. LAUBEL, SØREN E. LARSEN, HANS L. IVERSEN

Department of Streams and Riparian Areas, National Environmental Research Institute, Vejlsøvej 25, DK-8600 Silkeborg, Denmark

e-mail: bkr@dmu.dk

BJARNE HANSEN

Danish Institute of Agricultural Sciences, Department of Crop Physiology and Soil Science, Research Centre Foulum, PO Box 50, DK-8830 Tjele, Denmark

Abstract Soil erosion (rill erosion) was measured in 88 Danish slope units during three winter periods (1993/94–1996/97) and 140 slope units during the winter periods of 1997/98 and 1998/99. The mean annual amount of soil mobilized by rill erosion per hectare slope unit exhibited large temporal variation, being highest in the wet and cold winter of 1993/94 (0.89 m^3 ha^{-1}) and lowest in the warmer and drier winter of 1997/98 (0.10 m^3 ha^{-1}). Average annual soil erosion amounted to 0.31 m^3 ha^{-1}, corresponding to 465 kg ha^{-1}. Estimated phosphorus (P) loss was 0.29 kg P ha^{-1}. The average annual volume of soil eroded differed significantly between four main types of land management practice, being highest for slope units cropped with winter cereals (0.36 m^3 ha^{-1}) and lowest for slope units with grass (0.00 m^3 ha^{-1}). A mass balance for two selected rill systems revealed that no sediment and particulate P (PP) escaped across a 29 m wide buffer zone, whereas 38% of soil and 68% of PP passed through a 0.5 m wide buffer zone.

INTRODUCTION

The use of phosphorus (P) fertilizer and increasing livestock production have augmented soil P content of European agricultural land from very low to medium and high levels during the last century (Sibbesen & Runge-Metzger, 1995; Sibbesen & Sharpley, 1997). At the same time, eutrophication problems have accelerated in many European rivers and lakes (Kristensen & Hansen, 1994). Reports over the past two decades have provided convincing evidence for enhanced soil erosion on arable land which is attributed to increased production intensity and changes in the timing of cultivation, especially in combination with winter cereals (Colbourne & Staines, 1985; Sibbesen *et al.*, 1995).

The importance of diffuse P loss from agricultural land has increased during the last two decades in Denmark and many other European countries due to the effective control and treatment of point-source discharge of P (e.g. Kronvang *et al.*, 1996). There is therefore an urgent need to quantify dissolved P and particulate P loss from agricultural land to surface water via various hydrological pathways (e.g. combined soil erosion and surface runoff and subsurface drainage water). This will help to differentiate source areas of diffuse P loss within entire catchments and thereby enable implementation of proper management measures to combat diffuse P loss.

In this paper, we quantify rill erosion in Denmark and assess the importance of rill erosion for soil and P loss to surface water. In addition, the effect of riverine buffer zones as a means of reducing soil and P loss to surface waters is presented.

THE SLOPE UNITS STUDIED

The investigation is based on 140 arable field slope units situated within twenty localities (Fig. 1). The slope units cover all landscape types, climate gradients and dominant soil types in Denmark. The dominant soils are alfisols and spodosols, with textural composition typically ranging from sand to loam (Fig. 1). The average slope of the 140 slope units is 7% (range: 2–20%) and median riverine buffer zone width is 8.3 m (range: 0.6–125 m). The dominant winter crop cover on the 140 field slope units was winter cereals (44%), untreated stubble (13%), permanent grass (10%), catch crops (10%), harrowed stubble (8%), Christmas trees (5%), winter rape (4%), ploughed (4%) and fallow (3%). The average annual precipitation and temperature in Denmark during the period 1961–1990 were 712 mm and 7.7°C, respectively (Fig. 1).

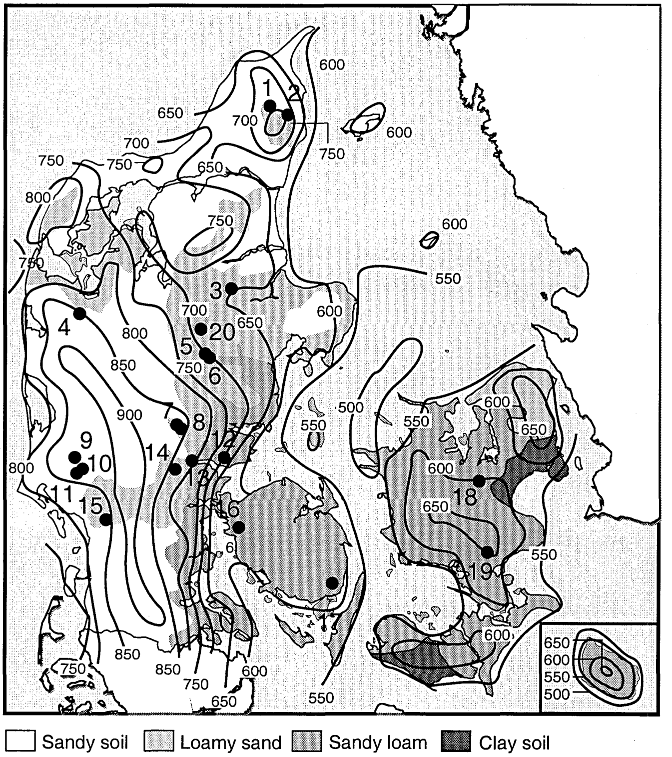

Fig. 1 The 20 localities investigated, dominant soil types and average annual precipitation in Denmark. The number of slope units situated in each location are (location: slope units): 1: 3, 2: 7, 3: 9, 4: 9, 5: 12, 6: 5, 7: 15, 8: 19, 9: 1, 10: 3, 11: 4, 12: 9, 13: 1, 14: 3, 15: 5, 16: 9, 17: 4, 18: 4, 19: 9, 20: 6.

METHODS

The volume of significant rill systems within each of the slope units studied was measured each spring (March) following the winter periods 1993/94–1996/97 (88 slope units) and the winters of 1997/98 and 1998/99 (140 slope units). At the same time each spring, information was collected on land use, crop type and buffer zone width for each of the slope units.

The delivery of soil to buffer zones and streams within each slope unit was surveyed in the field in early spring (March) following the winter periods 1997/98 and 1998/99. Detailed soil and P budgets were established for selected rill systems having different buffer zone widths, and deposition on the fields and in the buffer zones was determined. Between 150 and 200 cross-sections covering the entire length of the rill system were surveyed for rill width and depth (the latter at 10%, 50% and 90% of rill width). In addition, 150–200 cores were taken in a grid system set up to ensure covering the entire deposition area including both the field and buffer zone. The depth of deposited sediment was measured in each core sample. Three soil cores, each consisting of five composite samples, were collected to rill depth along the entire rill system and brought to the laboratory for analysis of bulk density and soil P content. A further five core samples were collected from the deposition zone on the field and 3–5 core samples were collected from deposited material in the buffer zone. Bulk density of soil and deposited material was measured by standard procedures in the laboratory. Total soil P content in each core sample was analysed by applying the procedure described in Svendsen *et al.* (1993). Eroded sediment volumes were estimated for two selected rill systems, each rill cross-section being assumed to represent half the distance to adjacent cross-sections.

The average volume of eroded soil was calculated as the geometric mean. Annual mean rill erosion and mean rill erosion for different field management practices were tested using the Kruskal-Wallis rank sum test (Hollander & Wolte, 1973). Sediment deposition relative to buffer zone width was examined for a selected slope unit, with sedimentation being estimated by the kriging method with a trend surface of degree 2 and with an exponential covariance function (Ripley, 1981).

RESULTS AND DISCUSSION

Rill erosion in Denmark

A large number of the slope units investigated exhibited no rill erosion (Fig. 2). In five of the six study years, more than fifty percent of the slope units were devoid of rill erosion. The number of slope units with rill erosion was highest in 1993/94 (52% of slope units) and lowest in 1997/98 (23%; Fig 2). Rill erosion was significantly greater (Kruskal-Wallis rank sum test; $p < 0.05$) in 1993/94 than in the other years studied.

The annual geometric mean soil volume mobilized via rill erosion was nine-fold greater in 1993/94 than in 1997/98 (0.89 m^3 ha^{-1} *vs* 0.10 m^3 ha^{-1}), varying from 0.17 to 0.29 m^3 ha^{-1} in the other years. Higher rill erosion in 1993/94 was attributed to the fact that winter 1993/94 was relatively cold (4.0°C) and humid (597 mm) with

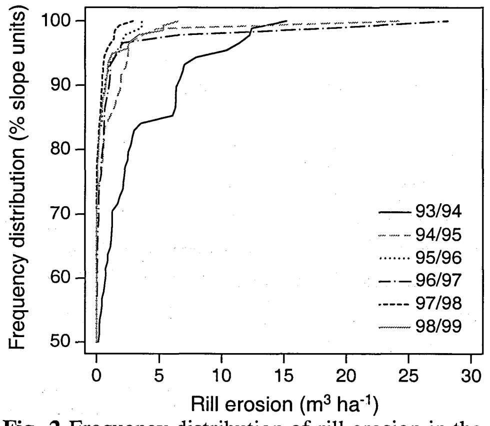

Fig. 2 Frequency distribution of rill erosion in the six study years, 1993/94–1998/99 (1993/94–1996/97: n = 88; 1997/98–1998/99: n = 140).

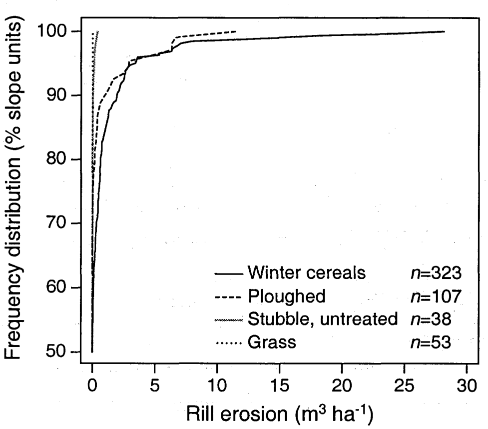

Fig. 3 Frequency distribution of rill erosion in four types of slope unit differing in management practice. Data are from the whole six-year period.

several thaw events (i.e. rain or melting of snow on frozen soil), while the winter of 1997/98 was relatively warm (5.6°C) and dry (413 mm).

The average annual soil erosion amounted to 0.31 m^3 ha^{-1} during the six-year study period, equivalent to 465 kg sediment per hectare. With an average P content of 630 mg P kg DW^{-1} (per kg dry weight) in the soil, P loss can be estimated to 0.29 kg P ha^{-1}. The average annual soil loss from potentially erodible areas in Denmark as measured in this study is considerably lower than that documented by Uhlen & Lundekvam (1988) for different regions of Norway (700–3000 kg ha^{-1}), but similar to the soil loss found in the UK (Boardman, 1990) and Sweden (Alström & Bergman, 1990).

Importance of management practice for rill erosion

Apart from climate, management practice was a significant determinant of rill erosion (Fig. 3). The geometric mean rill erosion for slope units classified into four types of management practice was 0.00 m^3 ha^{-1} (grass), 0.02 m^3 ha^{-1} (untreated stubble), 0.22 m^3 ha^{-1} (ploughed) and 0.36 m^3 ha^{-1} (winter cereals). The volume of soil eroded differed significantly between the four types of slope unit (Kruskal-Wallis rank sum test; $p = 0.05$).

Other factors undoubtedly also influence rill erosion, for example various soil properties and landscape features (cf. Morgan, 1988). We have not yet fully analysed the relationships between rill erosion and these factors, but intend to use the present observations to establish an expert system. The expert system should be used as a predictive tool, pinpointing which combinations of topography, geology, soil type and crop management may lead to soil erosion. Such an expert system could be used to advise Danish farmers on how to alleviate or avoid soil erosion problems.

Delivery of sediment and P to buffer zones and streams

A survey of soil delivery across the field edge to the buffer zone and across the stream edge to the surface water was conducted in the 140 slope units following the winter periods of 1997/98 and 1998/99. On average, surface runoff was observed at 63% of the slope units. Eroded soil entered the buffer zone at 30% of the slope units and was delivered to the surface water at 19% of the slope units.

Detailed measurements at two selected sites (rill system and adjacent buffer zone) demonstrated the importance of the buffer zone as a sediment and phosphorus trap (Fig. 4). At the site with a 29 m wide buffer zone, all sediment and P was retained. At the site with a 0.5 m buffer zone, in contrast, 38% of sediment and 68% of P from rill erosion passed through to the stream. Thus in the latter case a relatively high proportion of P was lost to the stream since the P-enriched fine sediment was transported for a longer distance than the more coarse (sandy) sediment, often all the way to the stream.

In both cases, a significant amount of sediment (430 kg and 4470 kg, respectively) was deposited at the down-slope part of the field before the buffer zone because of the decrease in slope gradient (Fig. 4).

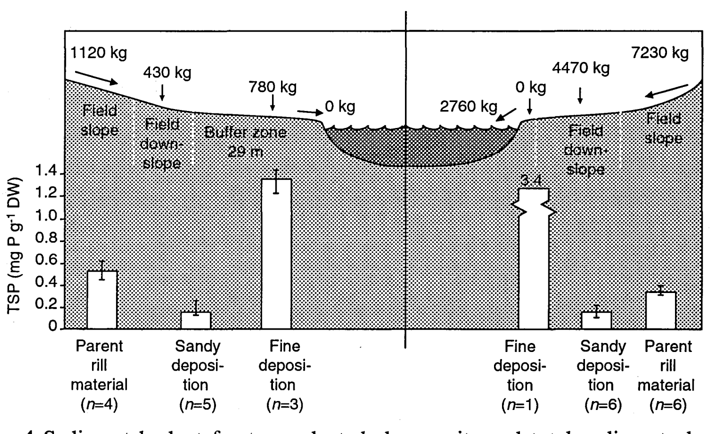

Fig. 4 Sediment budget for two selected slope units and total sediment phosphorus (TSP) in eroded and deposited sediments. The left-hand slope unit has a 29 m wide grass buffer zone grazed by cattle most of the year, while the right-hand slope unit has a 0.5 m wide buffer zone with mixed grass–herbaceous vegetation.

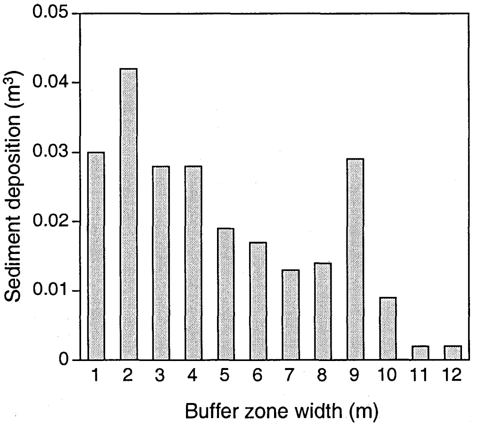

Fig. 5 Sediment deposition *vs* buffer zone width in a 27-m wide grass–herbaceous buffer zone.

Scenario for sediment and phosphorus retention in a buffer zone

In order to further evaluate the importance of buffer zone trapping efficiency, sediment and P retention in the buffer zone of a selected site was examined statistically using the kriging method. All sediment and P was retained within the first 12 m of the 27 m buffer zone where the slope gradient was 14% (Fig. 5). Phosphorus was retained equally effectively as sediment. Fifty-five percent of both sediment and P was retained in the first 4 m of the buffer zone (Fig. 5). A relatively high amount of sediment and P was deposited 9 m from the field, apparently due to a change in the buffer zone slope gradient.

From several such scenarios based on detailed measurements we hope to gain an understanding of what site-specific conditions and what magnitude of rill erosion would enable sediment and P to pass though different buffer zone types.

Several factors undoubtedly influence the sediment and P retention efficiency of buffer zones, including buffer zone width and slope, as well as flow rate, sediment load, grass height and density, and degree of vegetative submergence (Wilson, 1967).

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