BUFFER ZONES AS A SINK FOR SEDIMENT AND PHOSPHORUS BETWEEN THE FIELD AND STREAM: DANISH FIELD EXPERIENCES

Brian Kronvang[1], Anker Laubel[2], Søren E. Larsen[1], Hans E. Andersen[1] and Jørgen Djurhuus[3]

[1] *National Environmental Research Institute, Department of Freshwater Ecology, Vejlsøvej 25, DK-8600 Silkeborg, Denmark (BKR@DMU.DK).*
[2] *Vejle County, Department of Marine Environment, Damhaven 12, DK-7100 Vejle, Denmark.*
[3] *Danish Institute of Agricultural Sciences, Department of Crop Physiology and Soil Science, Research Centre Foulum, PO Box 50, DK-8830 Tjele, Denmark*

ABSTRACT

An investigation of rill erosion, surface runoff and storage of sediment and phosphorus in buffer zones was conducted during three winters (1997/98-1999/2000) on ca. 140 arable field slope units situated within twenty localities in Denmark covering all landscape types, climate gradients and dominant soil types. The dominant soils on the slope units are Alfisols and Spodosols, with textural composition typically ranging from sand to loam. The average slope of the 140 slope units is 7% (range: 2-20%) and median buffer zone width was 8.3 m (range: 0.6-125 m). The geometric mean annual rill erosion was 0.33 m^3 ha^{-1} equalling to 495 kg sediment ha^{-1} and 0.25 kg P ha^{-1}. The deposition of sediment on the field, in the buffer zone and delivery of soil to the stream was surveyed within the 140 slope units following three winters of 1997/98, 1998/99 and 1999/2000. Deposition of sediment in the buffer zone was observed in 31% (1997/98), 31% (1998/99) and 29% (1999/2000) of the slope units. Delivery of soil across the edge of the stream was observed in 23% (1997/98), 17% (1998/99) and 25% (1999/2000) of the 140 slope units. Median dissolved P concentration in surface runoff was 0.18 mg P l^{-1} (range: 0.029-16.294 mg P l^{-1}). A probability model was developed that enable us to predict the efficiency of different widths of buffer zones along stream channels to prevent delivery of soil material and associated phosphorus to the stream dependent on the sizes of rills within a slope unit.

KEYWORDS: Buffer zones, soil erosion, storage, grain sizes, phosphorus, streams, models.

INTRODUCTION

The use of phosphorus (P) fertiliser 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 & 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 (Kronvang et al., 2000).

Water erosion on field slopes and surface runoff are in many countries an important source areas and hydrological pathways for sediment and phosphorus delivery to surface waters (eg. Johnes and Hodgkinson, 1998; Verstraeten and Poesen, 2000). The recently adopted EU Water Framework Directive (EU, 2000) demands that a good ecological condition shall be established in streams and lakes during the coming 1-2 decades. Excess delivery of sediment and phosphorus to streams and lakes can prevent the establishment of a good ecological condition as sediment can damage spawning grounds for trout and salmon in streams and phosphorus can create eutrophication in both rivers and lakes (eg. Kronvang *et al*., 1993).

Therefore, many authors have looked into the possibility of trapping sediment and phosphorus in uncultivated buffer zones established along streams and lakes (eg. Dillaha *et al*., 1989). The efficiency of such buffer zones for trapping of sediment and sediment-associated phosphorus are well proven from experimental research on small field plots (eg. Uusi-Kämppä *et al*., 1998). Less research has been conducted on water erosion and buffer zones under natural field conditions.

We investigated the amount of rill erosion on ca. 135 slope units in Denmark during a 3 years period, together with a qualitative survey of the trapping effect of existing buffer zones along smaller streams. This paper gives details on the amount of water erosion (rill formation) on sloping agricultural fields in Denmark, the width of existing buffer zones and their potential for storing sediment and sediment-associated phosphorus. A logistic model was developed that enable a prediction of the efficiency of different widths of buffer zones along stream channels to prevent delivery of soil material and associated phosphorus to the stream dependent on the sizes of rills within a slope unit.

STUDY AREAS

The investigation is based on 140 arable field slope units situated within twenty study areas (Fig. 1). The slope units border smaller streams and were selected to be in risk for experiencing soil erosion. 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 riparian buffer zone width was 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 ground corrected precipitation and temperature in Denmark during the three winters studied (October-March) was 486 mm and 4.4 °C in 1997/1998, 635 mm and 3.1 °C in 1998/1999 and 588 mm and 3.9 °C in 1999/2000.

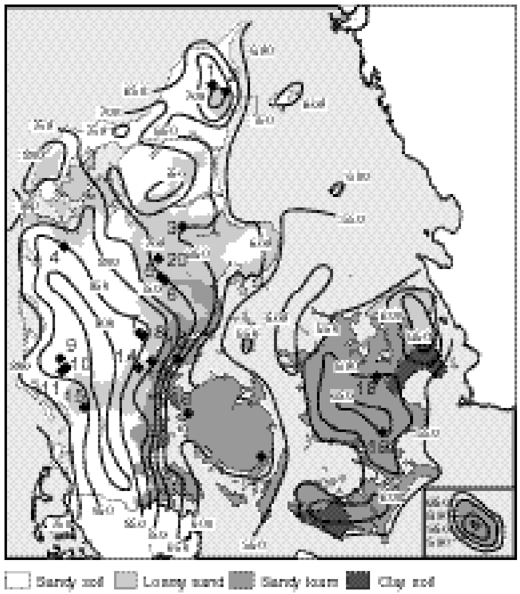

Figure 1 The 20 localities investigated, dominant soil types and average annual precipitation in Denmark.

METHODS

The ca. 140 slope units were visited twice during early spring each year (March). At one visit the amount of rill erosion on each slope unit was quantified. The other visiting team made a survey of each slope unit counting the number of rills in two size classes, counting number of sand deposits on the field, sites in buffer zones with sediment deposition and sites with delivery of sediment to the stream. A number of site specific characteristics were also measured and described, including length and slope of the field and buffer zone width and type. The volume of rill systems within each of the slope units was measured each spring (March) following the winter period of 1997/98 to 1999/2000. The volume of soil eroded on each field was quantified by measuring the dimension of each larger rill system by traversing the field. Smaller rill systems on the fields were classified into different size classes utilising standard average dimensions for calculation of total soil volume.

For the winters 1997/98 to 1999/2000, a number of characteristics related to erosion, deposition and sediment delivery to the buffer zone and stream were described at the same time in March, and information was collected on management practise of the slope units. Water samples were collected from surface runoff at 26 slope units in early March 1998 during a period with heavy rain. The water samples collected from surface runoff were analysed for dissolved P after filtering 100-500 ml of sample through pre-combusted and pre-weighed 1.2 µm glass microfibre filters. The concentration of dissolved P was measued by converting to dissolved reactive P using persulphate digestion in an autoclave (Koroleff, 1983). Dissolved reactive P was determined colorimetrically according to Murphy and Riley (1962).

Three soil cores, each consisting of 5 composite samples, were collected to rill depth along the entire rill system and brought to the laboratory for analysis. A further 5-8 core samples were collected from the deposition zone on the field and in the buffer zone. In total 199 sediment samples were collected. The sediment samples were dried at 105°C and analysed for total sediment P by applying the procedure described in Svendsen *et al*. (1993).

The relationship between explanatory variables and three rill erosion classes was examined by logistic regression (McCullugh & Nelder, 1989).

$$\log (p / (1 - p)) = a + b_1 x_1 + b_2 x_2 + ... + b_n x_n \qquad (1)$$

The estimated regression model was transformed to give a model for the probability of sediment delivery to buffer zone and stream, respectively.

$$p = 1 / [1 + \exp (-(a + b_1 x_1 + b_2 x_2 + ... + b_n x_n))] \qquad (2)$$

All parameters included in the presented logistic models are significant at $p<0.05$.

RESULTS AND DISCUSSIONS

Rill erosion on slope units

A large number of the slope units investigated exhibited no rill erosion (Table 1). In all three study years, more than fifty percent of the slope units were devoid of rill erosion (Table 1). The annual average soil volume mobilised via rill erosion was low in all three studied years both calculated for all slope units and for slope units experiencing rill erosion (Table 1). However, rill erosion was high at a few of the slope units studied possibly reflecting that these slope units are very high erosion risk areas (Fig. 2). The highest rill erosion volume was recorded after the winter of 1998/1999 (Table 1). This winter was also the one having the highest rainfall and being the coldest of the three winter periods studied.

Table 1 Geometric mean rill erosion volume in the three study years shown for all slope units and the percentage of slope units without sign of rill erosion. The precipitation and average temperature for the winter period (October-March) is also shown.

	N	Rill erosion (m3/ha)	Slope units with no rill erosion (%)	Winter rainfall (mm)	Winter temperature (°C)
1997/1998	141	0.14	57	486	4.4
1998/1999	138	0.30	61	635	3.1
1999/2000	139	0.24	46	588	3.9

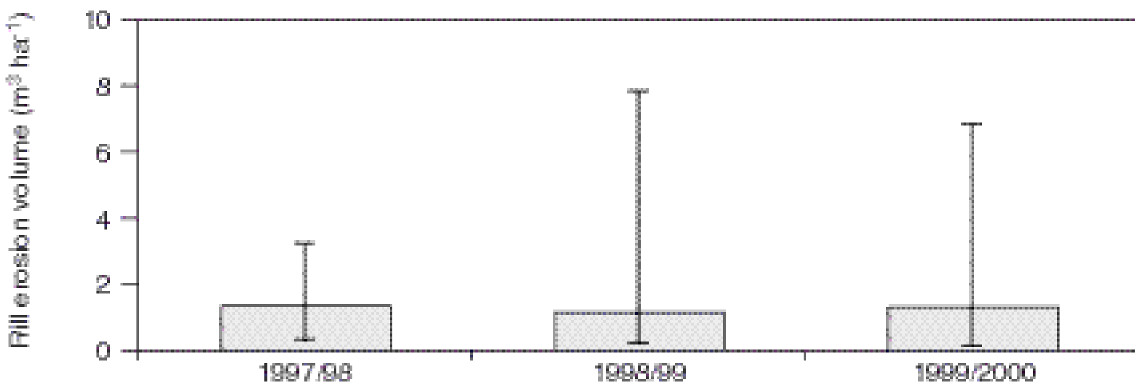

Figure 2 *Descriptive statistics of rill erosion volume for the three years studied shown for slope units with fields experiencing erosion. Bars represents 5% and 95% percentiles.*

Geometric mean annual soil erosion amounted to 0.33 m^3 ha^{-1} during the three-year study period, equivalent to 495 kg sediment per hectare. The P-content of eroded soil, deposited material in the sand cone and deposited fine sediment in buffer zones revealed a more than three fold P-enrichment of soil material from eroded soils on the slope unit to deposited fine sediment in the buffer zone (Fig. 3). With an average P content of 507 mg P kg^{-1} DW^{-1} in the eroded soil, the P-loss can be estimated to 0.25 kg P ha^{-1}. The average annual rill erosion loss from potentially erodible agricultural slope units in Denmark was considerably lower than the soil erosion documented by Uhlen & Lundekvam (1988) for different regions of Norway (700-3,000 kg ha^{-1}), but similar to the soil loss from rill erosion measured in UK (Boardman, 1990) and Sweden (Alström & Bergman, 1990).

Qualitative survey of sediment delivery to buffer zones and streams

Several factors influence sediment transport from field to streams among those being rill volume, down slope inclination, distance to buffer zone from rill outlet, buffer zone width, vegetation, etc. We addresses three main questions from our qualitative survey on the 140 slope units:

1. Which factors influence sediment delivery to the buffer zone?
2. Which factors influence sediment delivery to the stream?
3. Which factors influence the trapping efficiency of the buffer zone?

Furthermore, we will attemp to predict the probability (p) of sediment delivery to the buffer zone and stream based on different controlling factors. First, however, we will classify the rill erosion surveyed and describe the width of existing buffer zones on the 140 slope units during the three-year study period.

We divided the individual rill systems on slope units into three classes:
RILL class 0: No sign of rill erosion.
RILL class 1: Slope units with smaller rill systems developed (<10 cm in width).
RILL class 2: Slope units with larger rill systems developed (>10 cm in width).

The three classes of rill erosion experienced different average rill volumes as measured on the slope units during the three-year study period (Fig. 4A). The measured width of existing buffer zones on the investigated slope units varied from no buffer zone to grass buffer zones of up to 120 m width (Fig. 4B).

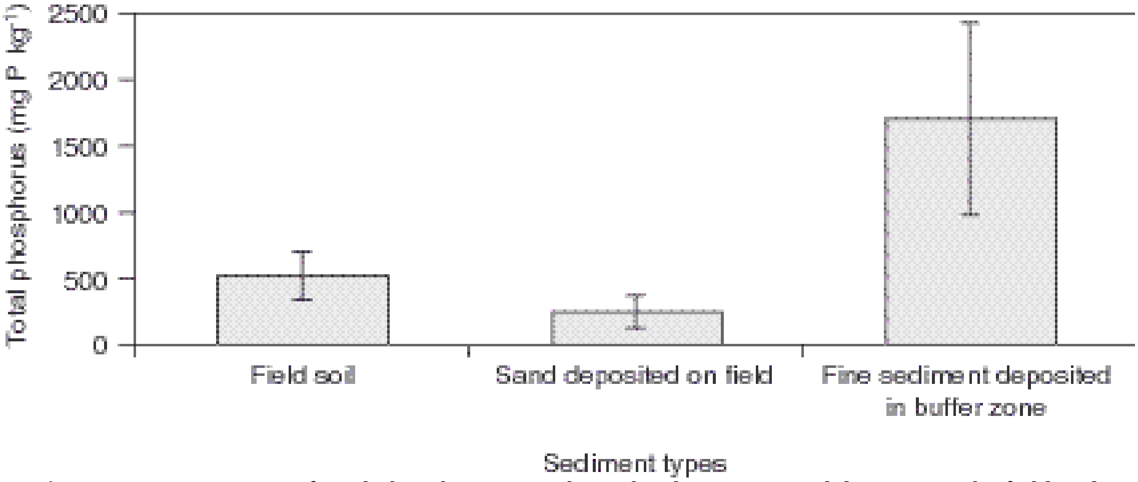

Figure 3 *Concentration of total phosphorus in soils on the slope unit, sand deposits on the field and fine sediment deposited in the buffer zone.*

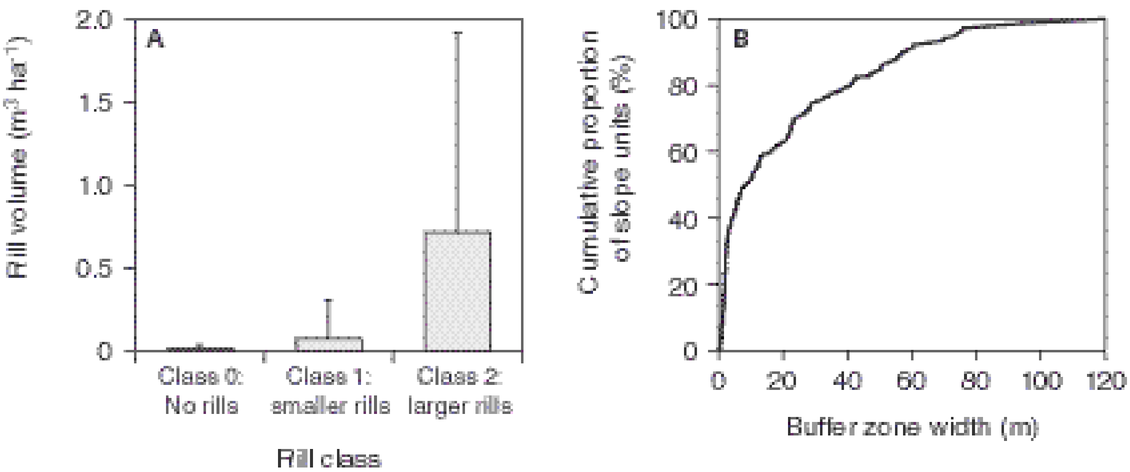

Figure 4 Measured rill erosion volume in the three classes of rill sizes (RILL class 0, 1 and 2) (A) and width of the buffer zones bordering the investigated slope units (B).

The frequency of smaller and larger rill systems, sand deposits on the field, sediment deposits in the buffer zone and sediment delivery to the streams during the three-year studied period is shown in Table 2. No major differences were recorded during the three years.

Table 2 Survey of rill erosion, sand deposition on the field before the buffer zone, sedimentation in the buffer zone and delivery of sediment to streams during three winter periods in 138-146 slope units in Denmark.

Year	N	Large rills (class 2)		Small rills (class 1)		Sand deposits in the field		Sediment deposited in the buffer zone		Sediment delivery to streams	
		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
1998/1999	138	20%	80%	67%	33%	63%	37%	31%	69%	23%	77%
1999/2000	139	29%	71%	62%	38%	57%	43%	31%	69%	17%	83%
2000/2001	146	34%	66%	58%	42%	55%	45%	29%	71%	25%	75%

Sediment and sediment-associated phosphorus delivery to the buffer zone

Sediment delivery to a buffer zone from a field with rill erosion depends on the rill volume and the factors controlling the transport and deposition of sediment on the field. Sediment enters the buffer zone when sediment is transported downhill without having the possibility to fully deposit on the field itself.

The best multivariate logistic regression model describing sediment delivery to the buffer zone is:

$$P_{BZ} = 1 / [1 + \exp(-1.54 + 5.48 (X) + 2.22 (Y))] \quad (3)$$

$$R^2 = 0.57 \qquad p<0.001 \quad N = 410 \quad (4)$$

Where P_{BZ} is the probability that sediment is delivered to the buffer zone, X = RILL class 0 and Y = RILL class 1. X will be zero if the slope unit is of RILL class 1 or 2 and else one. Y will be zero if the slope unit is of RILL class 0 or 2 and one if the RILL class is 1.

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Therefore, the probability for sediment delivery to the buffer zone was 0.02 in cases with no rills (class 0), 0.34 in cases with small rills (class 1), and 0.82 in cases with large rills (class 2) on the field. Other factors such as down slope inclination and the existence of an impermeable soil layer in the soil could be included in the model but did not improve its R^2 value.

Sediment and sediment-associated phosphorus delivery to the stream

Sediment transport through the buffer zone and delivery to the stream depends on the previous mentioned factors and factors like width, vegetation and infiltration capacity of the soil in the buffer zone.

The best multivariate logistic regression model describing sediment delivery to the streams is:

$$P_{stream} = 1/[1 + \exp(-0.674 + 4.07 (X) + 1.76 (Y) + 0.0329 W_{BZ} \quad (5)$$

$$R^2 = 0.41 \qquad p<0.001 \quad N=394 \quad (6)$$

Where P_{stream} is the probability for sediment delivery to the stream, X = RILL class 0, Y = RILL class 1, and W_{BZ} is the buffer zone width. X will be zero if the slope unit is of RILL class 1 or 2 and else one. Y will be zero if the slope unit is of RILL class 0 or 2 and one if the RILL class is 1.

A probability plot of showing the influence of rill class and buffer zone width on the probability of sediment delivery to streams fro m the slope units are shown in Figure 5.

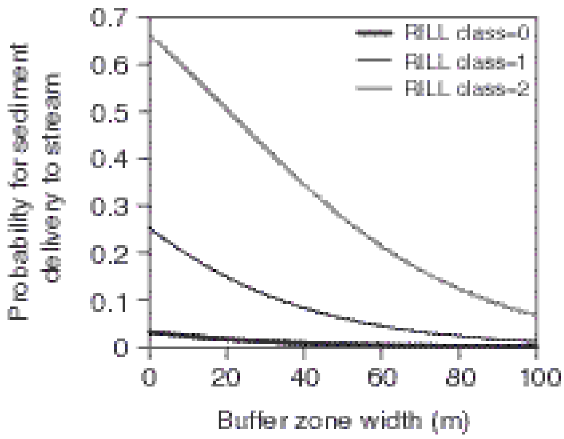

Figure 5 Probability plot showing the influence of rill class and buffer zone width on the probability for sediment delivery to the steam.

Delivery of dissolved phosphorus with surface runoff from fields

The concentration of dissolved phosphorus (DP) was analysed in surface runoff crossing the stream edge from 28 slope units in March 1998. The median concentration of DP in surface runoff was 0.18 mg P l^{-1} (Table 3). This is much higher than the concentration of DP measured in water leaching from the root zone on sandy arable soils (0.022 mg P l^{-1}) and loamy arable soils (0.010 mg P l^{-1}) under normal conditions in Denmark (Kronvang et al., 2002). The observed DP concentrations varied from 0.029-16.294 mg P l^{-1} and 43% of the observations had DP concentrations above 0.2 mg P l^{-1}. Such high P-concentrations are above the eutrophication limit for lakes (Kristensen and Hansen, 1994) and show that risk areas for DP-loss exists in the landscape as is also the case for sediment and sediment-associated P-loss.

Similar high concentrations of dissolved phosphorus in surface runoff have been documented in other studies (eg. Sharpley et al., 1982; Gillingham and Thorrold, 2000). The causes of high dissolved P concentrations in surface runoff are undoubtedly desorption from soils high in P-status, recently applied animal manure or manure from grazing domestic animals. Plot experiments with buffer zones have also in some cases shown very high losses of dissolved P even though the buffer zone trapped considerably amounts of sediment and sediment-associated P (Uusi-Kämppä et al., 2000).

Table 3 Average, median and range of the concentrations of dissolved phosphorus in surface runoff sampled at the edge of the stream from 28 slope units in March 1998.

	Average	Median	Range
Dissolved P (mg P l^{-1})	0.871	0.181	0.029-16.294

CONCLUSIONS

The average annual rill erosion in potential erosion risk areas in Denmark was in this study found to be 495 kg/ha during the three years studied. The average annual loss of P from agricultural areas in Denmark has been estimated to 0.4-0.5 kg P ha^{-1} (Kronvang *et al*., 2001). The mobilisation of sediment-associated P on potential erosion risk fields in Denmark amounted to only 0.25 kg P ha^{-1} during the 3-year study period. This is less than half of the total P-loss to Danish freshwater. A large proportion of the mobilised sediment and sediment-associated P on the slope units will be trapped on the slope unit or in the existing buffer zones. Thus, rill erosion and delivery of sediment and sediment-associated P in years with normal precipitation and snow (like the three studied years) can not generally be considered to be a large P-source and pathway.

A number of the studied slope units experienced high rill erosion and subsequent transport of sediment and sediment-associated P towards streams. These critical source areas can locally deliver high sediment and sediment-associated P to streams and hence hinder the fulfilment of a good ecological status as demanded by the EU Water Framework Directive. The local source areas have to be pointed out and measures implemented to decrease the mobilisation of sediment and/or the delivery to streams. One such measure is to reinstate natural buffer zones along streams and lakes a measure that will further help to improve the ecological status of riparian areas and streams.

In this study we have developed a probability model for sediment delivery to streams depending on a classification of critical source areas into soil erosion categories. The model can assist catchment managers in planning the necessary buffer zone width to reduce losses of sediment and sediment-associated P to streams. Unfortunately, we also measured very high concentrations of dissolved P in surface runoff from Danish fields to streams. Establishing buffer zones along stream margins will not be as efficient against dissolved P as sediment-associated P. Only a proper handling (timing of year) and spreading (incorporation in soil) of animal manure on erosion risk areas will help to reduce the loss of dissolved P to streams with surface runoff.

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