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RIPARIAN BUFFER STRIPS AS A MULTIFUNCTIONAL TOOL IN AGRICULTURAL LANDSCAPES

Phosphorus Load to Surface Water from Bank Erosion in a Danish Lowland River Basin

Brian Kronvang,* Joachim Audet, Annette Baattrup-Pedersen, Henning S. Jensen, and Søren E. Larsen

Phosphorus loss from bank erosion was studied in the catchment of River Odense, a lowland Danish river basin, with the aim of testing the hypothesis of whether stream banks act as major diffuse phosphorus (P) sources at catchment scale. Furthermore, the study aimed at analyzing the impact of different factors influencing bank erosion and P loss such as stream order, anthropogenic disturbances, width of uncultivated buffer strips, and the vegetation of buffer strips. A random stratified procedure in geographical information system (GIS) was used to select two replicate stream reaches covering different stream orders, channelized vs. naturally meandering channels, width of uncultivated buffer strips (≤2 m and ≥10 m), and buffer strips with different vegetation types. Thirty-six 100-m stream reaches with 180 bank plots and a total of 3000 erosion pins were established in autumn 2006, and readings were conducted during a 3-yr period (2006–2009). The results show that neither stream size nor stream disturbance measured as channelization of channel or the width of uncultivated buffer strip had any significant ($p < 0.05$) influence on bank erosion and P losses during each of the 3 yr studied. In buffer strips with natural trees bank erosion was significantly ($p < 0.05$) lower than in buffer strips dominated by grass and herbs. Gross and net P input from bank erosion amounted to 13.8 to 16.5 and 2.4 to 6.3 t P, respectively, in the River Odense catchment during the three study years. The net P input from bank erosion equaled 17 to 29% of the annual total P export and 21 to 62% of the annual export of P from diffuse sources from the River Odense catchment. Most of the exported total P was found to be bioavailable (71.7%) based on a P speciation of monthly suspended sediment samples collected at the outlet of the river basin. The results found in this study have a great importance for managers working with P mitigation and modeling at catchment scale.

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Quantification of phosphorus (P) sources to surface waters at catchment scale involves a range of both point and diffuse emissions (Sharpley and Rekolainen, 1997; Heathwaite et al., 2005; Kronvang et al., 2007). In many developed countries around the world, diffuse P losses are today the dominant source in P budgets at river basin or catchment scale (Kronvang et al., 2007; Maguire et al., 2009). River basin managers need to establish knowledge of major diffuse P sources to cost-effectively combat the eutrophication problem in surface waters (Haygarth et al., 2009). Phosphorus models are one of the methods used by river basin managers to quantify the magnitude of different P pathways (Schoumans et al., 2009). Stream bank erosion is, however, seldom included in these models even though recent investigations have suggested bank erosion to be an important P source (Hasholt, 1988; Laubel et al., 2003; Kronvang et al., 2005; Zaimes et al., 2008).

Hundreds of River Basin Management Plans are currently being developed and adopted as part of the European Union's Water Framework Directive to secure at least a good ecological quality of all natural water bodies (EC, 2000). Phosphorus loadings from point and nonpoint sources are one of the most important water quality problems in surface waters. For example, the objectives for a good ecological quality in Danish shallow and deep lakes are set for summer chlorophyll *a* concentrations being transformed into an in-lake average summer total P concentration of 25 μg P L^{-1} for deep lakes and 70 μg P L^{-1} for shallow lakes (Danish Ministry of Environment, 2010). The maximum allowable concentrations of total P in inflowing waters to lakes can be calculated for each individual lake, utilizing lake models that takes the in-lake retention into consideration (Hejzlar et al., 2009) to not exceed the target concentrations for lake water P. The setting of such a strict ecologically driven P threshold for inflowing waters to lakes demands a knowledge on the P budget, importance of P sources, and the magnitude of diffuse P pathways within the lake catchment. Another important factor is the bioavailability of the P forms that enters the lake (e.g., Egemose and Jensen, 2009). Managers need to quantify the P loss from all land uses in the catchment, including the importance of fluvial erosion and subaerial processes causing erosion and loss of sediment

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Abbreviations: DW, dry weight; GIS, geographical information system.

and particulate P from cohesive stream banks (Lawler et al., 1999; Couper, 2003; Julian and Torres, 2006; Lawler, 2008).

Bank erosion is a natural fluvial process and therefore the input of P with bank material may be regarded solely as a background P source under certain conditions. Large-scale drainage schemes of riparian agricultural land converting natural meandering streams to straightened, deepened, and widened streams, and the subsequent change and reduction in vegetation cover along streams, will decrease bank stability and enhance the bank erosion process (Lawler et al., 1999; Laubel et al., 2003; Zaimes et al., 2008; Collins et al., 2010; Raven et al., 2010). Moreover, decades of intensive agricultural production in the drained riparian areas along streams being either in crop rotation or grazed pastures have increased the P content of stream margin soils (Collins and Walling, 2007; Hoffmann et al., 2009; Stutter et al., 2009). The importance of the different natural and anthropogenic factors influencing bank erosion and the subsequent sediment and P loss to surface waters is seldom investigated, and more knowledge about the magnitude of this source is therefore of great interest. The objective of this study was to compare stream bank erosion and sediment and P loss along reaches representing a gradient in watercourse forms (meandering contra channelized), stream types (three groups of stream orders; Strahler, 1957), undisturbed buffer zone width (narrow and wide), and buffer zone vegetation (low and high). Based on stream and buffer zone type, we hypothesized that the magnitude of stream bank erosion would generally increase with stream order, increase with anthropogenic disturbance of the stream channel and buffer zone vegetation, and decrease with width of uncultivated buffer zone. We also aim at quantifying the importance of bank erosion as a P source in this studied lowland River Odense catchment by establishing a P budget comparing the gross and net export of P from bank erosion with the measured total P export from the catchment. Finally, we utilized a chemical sequential extraction technique to evaluate the bioavailability of particulate P in bank sediment and suspended sediment transported in the river to downstream recipients as lakes and estuaries.

Materials and Methods

Study Catchment

The River Odense at Kratholm drains a catchment of 486 km^2 on the island of Funen, Denmark (Fig. 1). The most common landscape feature is moraine plains covered by moraine clay that was deposited by the base of the ice during its advance in the Weichsel glaciation period. The dominant soil type is loamy sandy soils (40%) and sandy clay soils (36%). Average annual precipitation amounts to 740 mm. The land use is dominated by arable land occupying 71% of the total area, followed by forested land (15%) and urban areas (8%). The population density in the catchment amounts to 124 inhabitants km^{-2}. The total length of stream channels in the catchment amounts to 352 km, equaling a stream density of 0.72 km km^{-2}. The altitude range within the catchment is 12 to 127 m, and all stream channels are therefore of the lowland stream type. The

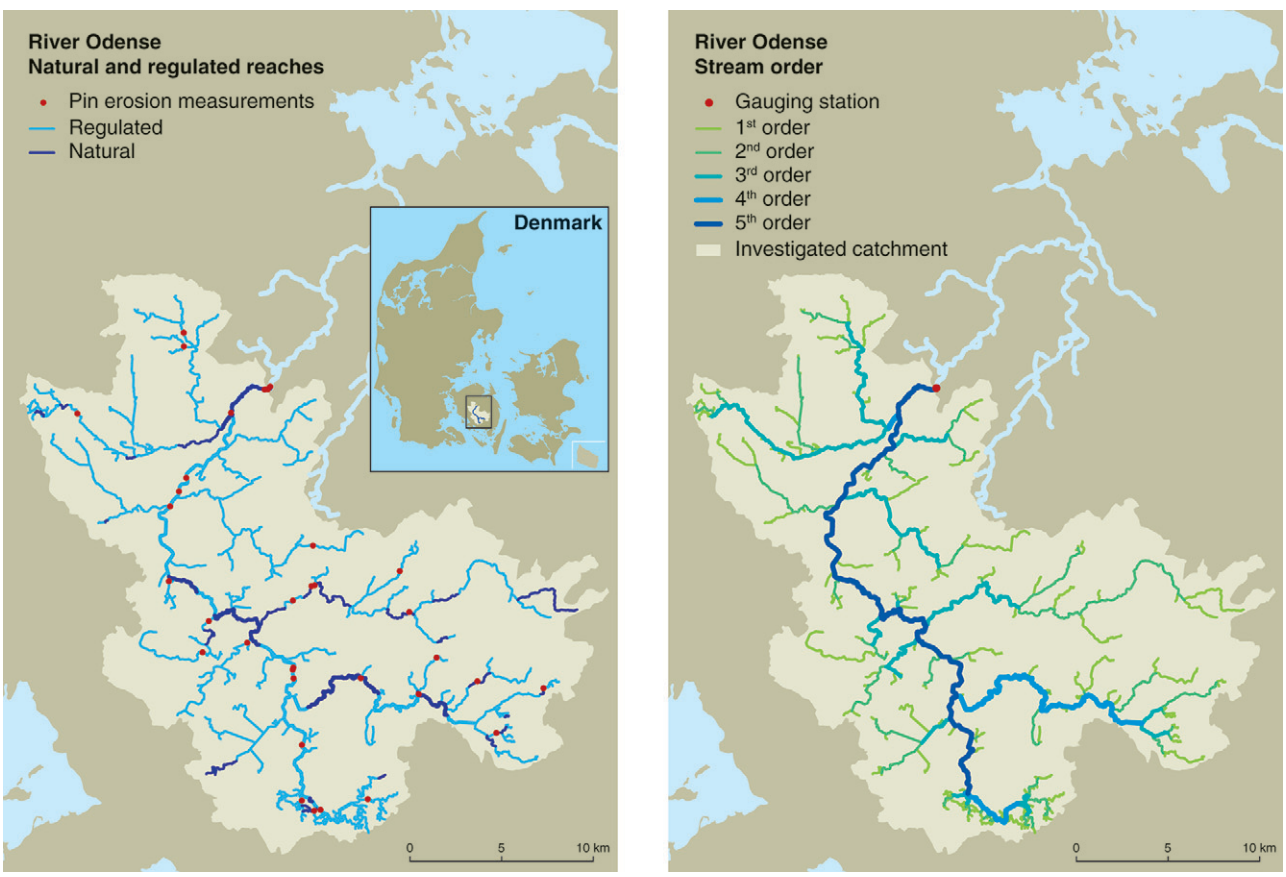

Fig. 1. The River Odense catchment on the island of Funen, Denmark, with a map (left) showing regulated and natural watercourses and the 36 sites for installation of erosion pins and a map (right) showing different stream orders and the gauging station installed at the catchment outlet. Inset map shows the location in Denmark.

average slope of the 36 watercourses involved in the study was 2.02 m km^{-1} (range: 0.01–7.29 m km^{-1}). In Denmark, uncultivated 2-m buffer strips along all natural watercourses and artificial watercourses having a high ecological objective were established in the Watercourse Act from 1991. Therefore, the watercourses involved in this study had at least a 2-m-wide buffer strip.

Experimental Design

A random stratified selection of different combinations of watercourse and buffer strip types were applied in the study. A preselection of different stream and buffer strip types were chosen for the field measurements of bank erosion. The reason behind the different types selected was to evaluate the importance of reinstating wider buffer zones along water courses in Denmark (e.g., 10-m uncultivated buffers), as an important part of the Danish policy measures in Action Plan III for the Aquatic Environment for reducing nutrient loss to the aquatic environment was to allow for 50,000 ha of uncultivated 10-m buffer zones along all 65,000-km stream types in Denmark (Kronvang et al., 2008). The different types selected were:

1. Artificially straightened watercourses vs. naturally meandering watercourses.
2. Stream orders: small—first and second orders; medium—third and fourth orders; and large—≥fifth orders (Fig. 1).
3. Narrow uncultivated buffer strip (≤2 m) or wide uncultivated buffer strip (≥10 m).
4. Low vegetation (grass or herbs) or high vegetation (trees and shrubs).

All combinations of types were represented in the experimental design except the combination of naturally meandering watercourses and narrow buffer strip, as these stream types always had a wide uncultivated buffer strip. A random, stratified selection of the 18 different combinations of stream and buffer zone types were conducted from a GIS analysis. A total of 10 watercourses, each 100 m long, were selected for each combination of types utilizing GIS maps. Finally, two replicate 100-m-long reaches of each combination of types, involving a total of 10 replicate plots, were randomly selected so a total of 36 stream reaches were included in the study design (Fig. 1). One of the selected reaches was, however, not measured due to active restoration of the stream channels during late autumn 2006.

Measurements of Bank Retreat and Accretion

Bank erosion was measured as bank retreat, utilizing 60-cm-long and 2-mm-diameter steel pins inserted at different heights into the banks during September 2006 (Fig. 2). Erosion pins have been widely used as a method for quantifying bank retreat and bank erosion processes (Lawler et al., 1999; Laubel et al., 2003; Zaimes et al., 2008). Each 100-m experimental stream reach consisted of five erosion pin plots, each consisting of three vertical lines of pins with a distance of 0.5 m between the lines (Fig. 2). In total, 3000 erosion pins were installed into 180 erosion pin plots by pushing them into the bank perpendicular to the bank face, leaving 40 to 60 mm exposed for ease of future location. Positive (erosion) and negative (accretion) pin readings were recorded within each pin plot in early spring during

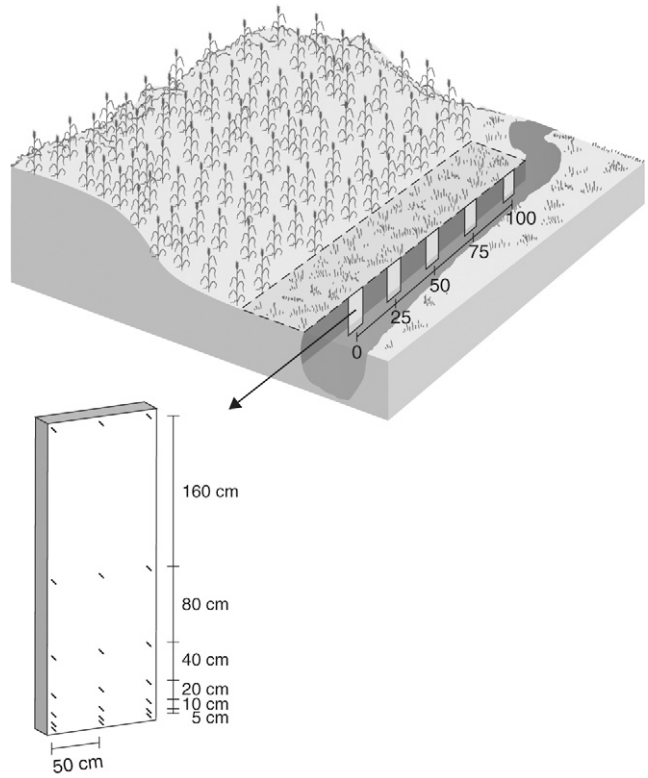

Fig. 2. The experimental setup along a 100-m study reach having five erosion pin plots, each having three vertical lines of erosion pins situated at different heights above the streambed.

the three study years: 2006 to 2007, 2007 to 2008, and 2008 to 2009. Previous studies of bank erosion in first- and second-order streams in Denmark have shown that erosion mainly takes place during the wet winter period where the banks are least protected by vegetation cover (Hasholt, 1988; Laubel et al., 2003). All pin readings were conducted with a metering stick and done by the same operator during all study years. Triplicate readings of bank retreat were done for each of a total of 96 pins placed in six different erosion pin plots to determine the uncertainty of the pin readings. The standard deviation of the three readings for each pin was calculated together with the average standard deviation. The result was an average standard deviation of 1.6 mm, giving an uncertainty of ±2 mm on the reading of erosion pins, which is a high resolution compared to that reported in other studies (Simon et al., 1999; Zaimes et al., 2008).

Survey and Grouping of Plant Communities in Buffer Strip Plots

The vegetation in the buffer strip is important for bank retreat processes, as their roots can stabilize the bank material. Therefore, the plant community was characterized within each of the 180 bank plots. A 1-by-1-m frame was placed at the edge of the stream channel, extending 1 m into the buffer strip. All species within the frame were identified to species level using the following abundance scale: 1: <1%, 2: 1 to 5%, 3: 5 to 10%, 4: 10 to 25%, 5: 25 to 50%, 6: 50 to 75%, 7: >75%. To analyze possible linkages between plant communities and bank erosion, a hierarchical clustering was performed using the Sorensen distance measure (PC-ORD 4.25, MjM Software,

Gleneden Beach, OR). Plots with fewer than three species were omitted from this analysis to achieve a robust interpretation of the data. A total of six distinct plant communities (C1–C6) were identified, but C6 was represented by only five plots and was therefore excluded from further analysis.

Weighted means of Ellenberg N and Ellenberg L were calculated for the investigated plots (Ellenberg et al., 1992). The Ellenberg values range from 1 to 9 (9 being high) and reflect the preferences that the species exhibit for nutrients (Ellenberg N) and light (Ellenberg L), respectively. Low values indicate preference for low amount of nutrients and light, whereas high values indicate preference for high amounts of nutrients and light.

Laboratory Analysis

Composite samples of bank material were collected from each 100-m stream reach in spring of 2007. One sample of bank material was collected from 20 cm above the streambed, and another bank sample taken at 60 cm above the streambed. Core sampling was conducted within each of the five erosion pin plots, taking three subsamples within each plot to a depth of 5 cm. Bank material bulk density was measured on 105°C-dried material taken as composite core samples on each of the study reaches. Bank material from each of the 36 reaches was analyzed for total P content by the method described in Svendsen and Kronvang (1993).

The composition of particulate P forms in bank material and river suspended matter (see sampling procedure below) was analyzed by a five-step sequential extraction protocol (Psenner et al., 1984; Paludan and Jensen, 1995), where first loosely adsorbed P and iron-bound P is removed by 1-h extraction in deionized water and in a solution of 0.11 M bicarbonate/0.11 M dithionite, respectively. Afterward, leachable organic P, humic-bound P, and P adsorbed to aluminum oxides and clay was removed by an 18-h extraction in 0.1 M NaOH. The two final steps remove first calcium-bound P in 0.5 M HCl and second, after combustion of the sediment residue, recalcitrant organic P by boiling in 1 M HCl. Loosely adsorbed P, iron-bound P, and leachable organic P are considered available for algae growth under the conditions that prevail in streams, lakes, and estuaries (for discussion of bioavailability, see Egemose and Jensen, 2009).

Statistical Methods

Mean annual stream bank erosion rates (positive pin readings) and accretion rates (negative pin readings) were calculated from the pin readings within each pin plot. The absolute pin readings were natural log-transformed before averaging due to the right-skewed distribution (geometric mean). Mean bank erosion values per pin plot were back-transformed to the original scale by using the formula: $\exp(\text{mean}) \times \exp(0.5 \times \text{SD} \times 2)$.

Mean annual stream bank erosion rates in the River Odense for all plots and for different stream types and buffer strip types were calculated from the back-transformed mean bank erosion on the plot scale. The mean values are given as mm yr^{-1} together with the standard error of the mean (arithmetic mean). Testing for differences in mean rates between stream types and buffer strip types was done by applying pair-wise tests using Bonferroni correction for dependent tests. Statistical tests were done on bank erosion data from plots transformed by natural logarithm due to the right-skewed distribution (geometric mean). Data were accepted to be Gaussian distributed after transformation using the Shapiro–Wilk test (Shapiro and Wilk, 1965), and variances were homogenous using Bartlett's test (Snedecor and Cochran, 1989).

Calculation of Gross and Net Sediment and Phosphorus Loss

Annual gross sediment delivery to the streams was calculated based on the geometric average of measured bank erosion rates from positive pin readings (mm yr^{-1}) multiplied by the plot area and the bank material bulk density. Average annual rates of gross bank erosion (in kg km^{-1} of stream) for the 18 categories of reaches (i.e., combinations of stream type, Strahler stream order, height of vegetation, and width of buffer zone) were then calculated utilizing the 10 erosion pin plots for each stream type. The total channel length of each stream type in the River Odense catchment was calculated from GIS maps and aerial photographs (Table 1). The length of each stream type was then multiplied with the calculated average annual gross bank erosion of sediment per kilometer of stream.

The average concentration of total P in stream bank material for each stream type was multiplied by the gross sediment loss to yield an annual gross total P load derived from bank erosion to the stream channels within the River Odense catchment. The net sediment export from the River Odense catchment was calculated by subtracting the amount of accretion of sediment per stream type extrapolated to the entire catchment from the calculated gross sediment input from bank erosion to the entire River Odense catchment. Similarly, the net total P export from the River Odense catchment from bank erosion was calculated by subtracting the total P content in deposited sediment (200–400 mg P kg^{-1} dry weight [DW]) from the gross total P input from bank erosion.

Measurements of Discharge and Phosphorus Export

Daily mean discharge was calculated for the study period (2006–2009) based on stage–discharge relationships developed for a long-term (1917) hydrometric station at Kratholm in the River Odense. Instantaneous discharge was measured every month, and water sampling was conducted with a combination of automatic sampling equipment (daily sampling) and grab sampling (fortnightly). The export of total P from the River Odense catchment was calculated from a linear interpolation of daily concentrations being multiplied with daily discharge as described by

Table 1. Stream length for the different categories of stream type and Strahler order.

Stream type	Strahler order	Length
		km
Natural	1–2	19.3
	3–4	24.9
	5	11.6
Regulated	1–2	208.5
	3–4	59.6
	5	26.5

Kronvang and Bruhn (1996). The precision associated with this P load calculation method will depend on the frequency of water sampling but is often within ±10 to 15% when having fortnightly water sampling in a catchment of the size of the River Odense (Kronvang and Bruhn, 1996). Source apportionment for calculation of the P loss from diffuse sources was conducted by extracting point source discharges of P within the catchment from the measured export of total P at the Kratholm river station as described by Kronvang et al. (2005). Suspended sediment samples were collected at the Kratholm station in the River Odense on a nearly monthly basis during the first study year by deploying an in situ passive sediment sampler described by Laubel et al. (2002). Samples for total P were dried (105°C, 24 h), while samples for P-pool distribution were kept cold (<5°C) and oxic until analysis (within 1 mo from sampling).

Results

Plant Communities in Buffer Strips

A total of five distinct plant communities (C1–C5) were identified in the investigated buffer strip plots. Cluster 1 was represented in 30 plots, Cluster 2 in 14 plots, Cluster 3 in 35 plots, Cluster 4 in 65 plots, and Cluster 5 in 18 plots. The most abundant species within each of the identified clusters is given in Table 2. The species richness was not significantly different among clusters (ANOVA $p > 0.05$), whereas Ellenberg N and Ellenberg L were significantly different (ANOVA $p < 0.05$). Ellenberg N was significantly lower in Clusters 1 (average 6.7) and 2 (average 5.5) than in Clusters 3 (average 7.1), 4 (average 7.0), and 5 (average 7.1; Bonferroni t test, $p < 0.05$). Similarly, Ellenberg L was significantly lower in Clusters 1 (average 5.4) and 2 (average 5.1) than in Clusters 3 (average 6.4), 4 (average 6.6), and 5 (average 6.7; Bonferroni t test, $p < 0.05$).

Quantifying Bank Erosion along Different Stream and Buffer Strip Types

Average annual bank erosion rates in 175 erosion pin plots ranged between 25 and 36 mm yr^{-1} during the 3-yr study period (Table 3). The observed median annual bank erosion rates indicated a relationship to the water flow from the catchment being highest during the wet Year 1 (2006–2007) and lowest in the dry Year 2 (2008–2009).

The 18 different combinations of stream channel and buffer strip types together with information on plant communities were statistically tested for differences in annual average bank erosion per plot by applying pair-wise tests using Bonferroni correction for dependent tests. The hypothesis that stream channels with narrow uncultivated buffer strips (≤2 m) had higher bank erosion rates than stream channels having a wide uncultivated buffer strip (≥10 m) could not be accepted statistically, as no significant ($p < 0.05$) differences were detected (Tables 4 and 5). Bank erosion rates were not statistically different between the three groups of stream orders ($p < 0.05$), nor could a statistically significant difference be obtained between straightened and naturally meandering stream channels (Table 4). Significant differences ($p < 0.05$) in bank erosion rates were found between stream channels with buffer strips of different vegetation types (high or low) and plant community types (Table 5).

Annual Gross and Net Phosphorus Input to Surface Waters from Bank Erosion

The total P content was relatively high in bank material, averaging 712 mg P kg^{-1} DW at 20 cm above the streambed and 723 mg P kg^{-1} DW at 60 cm above the streambed (Fig. 3). The total P content of bank material was not significantly different ($p = 0.67$) between the two heights above the streambed where soil samples were taken. The distribution of P forms in the bank material was analyzed in seven composite samples

Table 2. The relative abundance of the five most abundant species in the identified clusters.

Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5	
Species	%	Species	%	Species	%	Species	%	Species	%
Mercurialis perennis L.	13.6	*Agrostis capillaries* L.	16.1	*Urtica dioica* L.	14.1	*Arrhenatherum elatius* (L.) J. Presl & C. Presl	15.3	*Alopecurus pratensis* L.	32.5
Petasites hybridus (L.) P. Gaertn., B. Mey. & Scherb.	7.8	*Galium odoratum* (L.) Scop.	12.1	*Aegopodium podagraria* L.	13.1	*Urtica dioica* L.	14.9	*Urtica dioica* L.	12.2
Aegopodium podagraria L.	7.5	*Acer platanoides* L.	10.5	*Galium aparine* L.	10.8	*Poa trivialis* L.	12.1	*Phalaris arundinacea* L.	8.6
Urtica dioica L.	7.1	*Melampyrum pratense* L.	7.3	*Poa trivialis* L.	9.9	*Elytrigia repens* (L.) Nevski	8.5	*Calystegia sepium* (L.) R. Br.	7.6
Galium aparine L.	5.8	*Galium aparine* L.	4.0	*Petasites hybridus* (L.) P. Gaertn., B. Mey. & Scherb.	8.3	*Galium aparine* L.	7.1	*Galium aparine* L.	7.6

Table 3. Average gross annual and median annual bank erosion in the River Odense catchment as measured from positive pin readings in 175 erosion pin plots compared with annual (October–September) and winter (October–March) runoff from the catchment at the Kratholm hydrometric station.

Erosion and runoff	Year 1	Year 2	Year 3
Average bank erosion (mm)	36	25	26
Median bank erosion (mm)	27	16	16
Annual runoff (mm)	450	302	186
Winter runoff (mm)	313	229	139

Table 4. Bank erosion at two different stream types regarding stream order and degree of channel modification. Calculations are based on data from erosion plots.

Stream type	Streambank erosion rate†							
	Year 1	SEM (*n*)	Year 2	SEM (*n*)	Year 3	SEM (*n*)	Avg. year 1–3	SEM (*n*)
	mm yr^{-1}							
Stream size								
First- and second-order streams	30a‡	2.7 (59)	19a	1.5 (60)	23a	3.7 (60)	24a	1.6 (179)
Third- and fourth-order streams	38a	6.0 (58)	25a	4.9 (54)	31a	4.8 (49)	31a	3.1 (161)
Fifth-order streams	46a	8.7 (51)	42a	11 (52)	32a	6.9 (53)	40a	5.2 (156)
Degree of channel modification								
Channelized streams	34a	4.2 (113)	25a	3.8 (109)	30a	4.1 (105)	30a	2.3 (327)
Natural streams	45a	6.3 (55)	33a	8.6 (57)	25a	4.2 (57)	34a	3.9 (169)

† Year 1: 2006–2007, Year 2: 2007–2008, Year 3: 2008–2009; *n*: number of observations.

‡ Different letters (a, b, c) indicate significant differences ($p < 0.05$) among different stream types within the two groups tested.

Table 5. Bank erosion at three different buffer strip types regarding width of uncultivated buffer strip, high or low vegetation in buffer strip, and buffer strip plant types. Calculations based on data from erosion plots.

Stream type	Streambank erosion rate†							
	Year 1	SEM (*n*)	Year 2	SEM (*n*)	Year 3	SEM (*n*)	Avg. year 1–3	SEM (*n*)
	mm yr^{-1}							
Buffer strip width								
Streams with narrow buffer strips	26a‡	2.1 (53)	15a	1.0 (50)	27a	4.6 (45)	22a	1.7 (148)
Streams with wide buffer strips	41a	7.6 (60)	35a	6.8 (59)	32a	6.2 (60)	36a	4.0 (179)
Buffer strip vegetation height								
Streams with high vegetation	30a	4.1 (85)	24a	5.7 (87)	21a	3.2 (84)	25a	2.6 (256)
Streams with low vegetation	46b	5.6 (83)	33b	5.2 (79)	36b	5.2 (78)	38b	3.1 (240)
Buffer strip plant types								
Streams with Plant Type 1	25ab	2.9 (30)	18ab	2.5 (30)	17ab	4.6 (30)	20b	2.0 (90)
Streams with Plant Type 2	16a	2.6 (14)	8.2a	1.1 (14)	7.6a	0.90 (14)	11a	1.1 (42)
Streams with Plant Type 3	42abc	11 (29)	38ab	16 (29)	27bc	6.6 (27)	36bc	7.0 (85)
Streams with Plant Type 4	47c	6.9 (64)	31b	5.5 (64)	33bc	6.0 (62)	37c	3.6 (190)
Streams with Plant Type 5	41bc	8.7 (18)	39b	12 (16)	40c	7.4 (17)	40c	5.4 (51)

† Year 1: 2006–2007, Year 2: 2007–2008, Year 3: 2008–2009; *n*: number of observations.

‡ Different letters (a, b, c, ab, ac, abc) indicate significant differences ($p < 0.05$) among the three different tested buffer strip types.

(representing different sampling dates and with an average P content of 775 mg kg^{-1} DW; data not shown). Iron-bound P contributed >50% to the total pool in all samples and the distribution of forms resembled that found in suspended sediment (Fig. 4; also see below).

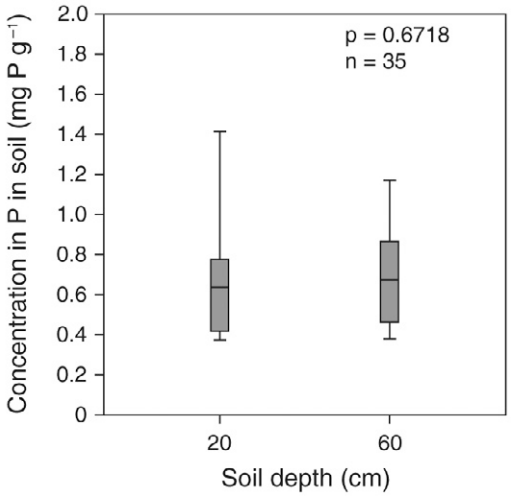

Fig. 3. The total phosphorus content of stream bank material analyzed from 35 composite bank material samples taken at two heights above the streambed (20 and 60 cm), shown as the median content and the 5, 25, 75, and 95% percentiles.

The gross amount of P mobilized with bank erosion from the 18 different combinations of stream and buffer strip types is shown in Table 6 for all three study years. The gross P mobilization varied between stream types with a minimum annual mobilization amounting to 4.2 kg P km^{-1} stream channel and a maximum mobilization amounting to 167.0 kg P km^{-1} stream channel (Table 6).

Importance of Bank Erosion as Phosphorus Source at Catchment Scale

The gross P mobilization from bank erosion in the entire River Odense catchment was compared to the net export of total P from the catchment as measured at the monitoring station at the catchment outlet (Table 7). The gross P mobilization amounted to 13.8 to 16.5 t P during the three study years. Negative erosion pin readings show that part of the mobilized sediment and P are retained in the stream channels during the study period. The net P mobilization from bank erosion in the River Odense catchment amounted to 17 to 25% of the total P export from catchment during the three study years when P content in retained sediment was considered to be between

200 and 400 mg P kg^{-1} DW (Table 6). The importance of bank erosion as a diffuse P source shows that in the wet study year (2006–2007) 21 to 23% of the diffuse P loss can be attributed to bank erosion and in a dry year (2008–2009) 44 to 62% of the diffuse P loss is derived from bank erosion (Table 7).

The suspended sediment had a P concentration four times higher (average 3410 mg P kg^{-1} DW) than the bank sediment, but the distribution of P forms was very similar to that in bank sediment and did not vary much with season (Fig. 4). Most of the exported P in suspended sediment was bound to iron complexes (average: 59%), easily decomposable organic matter (11%), and loosely adsorbed P (1.7%), forms that are considered bioavailable (Fig. 4).

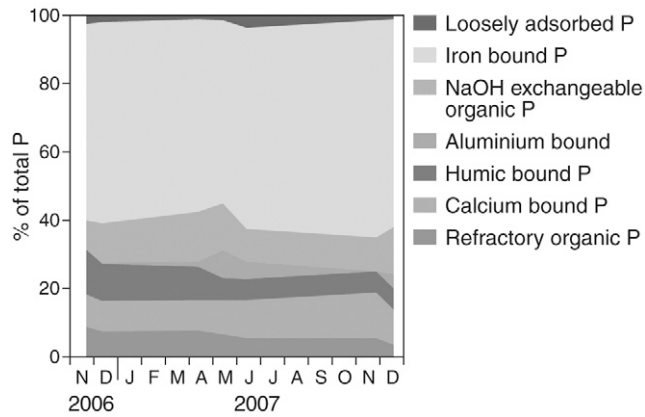

Fig. 4. Composition of particulate P forms in suspended sediment trapped in River Odense through year 2007. The P forms were analyzed by chemical sequential extraction. The first three forms, contributing >70% of total P, are considered bioavailable.

Discussion and Conclusions

The overall mean annual bank erosion rates observed in this study (31 mm yr^{-1}) were nearly three times higher than in a previous study of bank erosion in 15 Danish channelized first- and second-order stream banks (11 mm yr^{-1}) (Laubel et al., 2003). This study included several higher-order streams, but our findings of mean bank erosion in channelized first- and second-order streams with same bank height were still higher (24 mm yr^{-1}) than in the study by Laubel et al. (2003). One possible reason is that during this study we applied thin steel pins without a reference square of hard plastic pressed toward the banks (4.5 by 4.5 cm) that might have protected the banks from hydraulic erosion processes in the study by Laubel et al. (2003). The range found for mean bank erosion rates is, however, considerably lower than that observed in the bank erosion studies by Hooke (1980) and Lawler (1993), but in the same range as the findings by Bull (1997) in the River Severn in Wales and by Couper (2003) studying the influence of subareal activity on bank erosion in River Avon in England.

Stream bank erosion rates were found to be influenced by riparian land use in a 3-yr study of streams in Iowa, USA (Zaimes et al., 2008). The mean bank erosion rates were 15 to 46 mm yr^{-1} along riparian forest buffers, 41 to 106 mm yr^{-1} along grass filters, 104 to 122 mm yr^{-1} along rotational pastures, and highest along row-cropped fields 223 to 271 mm yr^{-1} (Zaimes et al., 2008). These results are generally much higher than our overall mean annual bank erosion results of 31 mm yr^{-1}. This might be due to difference in experimental design, as we applied a random selection of study reaches, whereas the study by Zaimes et al. (2008) only depicted severely eroding bare stream banks in their study based on a preliminary field survey. The relatively short study period (3 yr) means that major bank collapses that might occur with longer time intervals may not be systematically recorded with the erosion pin method

Table 6. Gross total P mobilized by bank erosion in River Odense catchment, Denmark. The stream network was stratified using GIS tools to obtain classification of streams according to their type (natural or regulated), Strahler order, height of vegetation (high: trees and shrubs; low: grass and herbs) and width of the buffer zone (wide ≥10 m and narrow ≤ 2 m).

Stream type	Strahler order	Vegetation height	Buffer zone width	P mobilized		
				2006–2007	2007–2008	2008–2009
				kg km^{-1}		
Natural	1–2	High	†	14.3	11.9	5.8
Natural	1–2	Low	†	35.0	20.1	28.0
Natural	3–4	High	†	44.0	34.7	19.6
Natural	3–4	Low	†	59.0	29.4	30.5
Natural	5	High	†	19.4	15.4	21.8
Natural	5	Low	†	55.8	23.6	12.4
Regulated	1–2	High	Wide	12.1	10.5	4.2
Regulated	1–2	Low	Wide	10.5	9.4	12.3
Regulated	3–4	High	Wide	8.6	7.9	7.9
Regulated	3–4	Low	Wide	18.9	32.5	44.1
Regulated	5	High	Wide	29.7	31.0	15.5
Regulated	5	Low	Wide	167.0	106.9	80.3
Regulated	1–2	High	Narrow	15.9	18.5	80.1
Regulated	1–2	Low	Narrow	22.8	17.6	11.0
Regulated	3–4	High	Narrow	8.6	4.9	8.0
Regulated	3–4	Low	Narrow	22.2	14.7	12.7
Regulated	5	High	Narrow	49.6	28.1	20.1
Regulated	5	Low	Narrow	31.8	25.9	29.3

† All natural streams had a vegetated buffer zone > 10 m.

utilized during this study. This might be another reason for the large difference between the observations of bank retreat in this study and the observations of bank erosion also conducted during 3 yr by Zaimes et al. (2008).

Our findings of the reduced stream bank erosion in banks with natural vegetation as indicated by occurrence of tree vegetation and forest floor communities with low preferences for nutrients and light is corroborated by the findings of reduced bank erosion in riparian forest buffers by Zaimes et al. (2008) and forested stream banks in the study by Laubel et al. (1999). Several other authors have given evidence from longer-term studies of bank erosion that land-use changes may affect slope stability and bank erosion (Hagerty et al., 1981; Brierley and Murn, 1997; Abernethy and Rutherfurd, 1998).

The importance of bank erosion as a source of P has seldom been documented, especially in catchment budgets. Zaimes et al. (2008) investigated the amount of P mobilization from stream banks along different riparian land use in Iowa, USA. They found P losses between 2 and 6 kg P km^{-1} yr^{-1} being lowest from riparian forests (2–6 kg P km^{-1} yr^{-1}) and highest from continuous riparian land use (71–123 kg P km^{-1} yr^{-1}) (Zaimes et al., 2008). Laubel et al. (2003) found an annual P loss from bank erosion of 0.23 to 0.28 kg P ha^{-1} catchment area in their study of 15 first- and second-order agricultural catchments and, having approximately 1 km of stream channel per square kilometer of catchment area as in this study, these findings amount to 23 to 28 kg P km^{-1} yr^{-1}. The findings in this study show a total P loss from gross bank erosion that amounts to 4.2 to 167.0 kg P km^{-1} yr^{-1} depending on year and type of stream and buffer zone (Table 5). The P loss from bank erosion in this study is thus comparable to the level found by Zaimes et al. (2008). Similarly, our findings of a gross P loss from bank erosion of 0.28 to 0.34 kg P ha^{-1} catchment area is at a similar level as the findings of Laubel et al. (2003).

In this study we investigated for the first time the net outcome of the bank erosion processes and the fluvial depositional processes. The positive (erosion) and negative (accretion) erosion pin readings made it possible to calculate a net contribution of P from bank erosion subtracting P sedimentation in the stream channels from the gross P input. Net P input from bank erosion amounted on average to 20 to 36% of the gross P input during the three study years. The difference in total P content between suspended sediment (average 3410 mg P kg^{-1} DW) and bank sediment (712–723 mg P kg^{-1} DW) is likely because bank sediment contains high proportions of sand-sized material having a very low P content, whereas suspended sediment often has high proportions of silt and clay-sized material being enriched in P.

Only a smaller part of the gross P input with soil material thereby seems to leave the catchment during the same year. This finding is in accordance with the findings of Collins and Walling (2007) in two study catchments in the United Kingdom (Tern and Pang/Lambourn) where fine sediment storage was found to represent a significant term in catchment sediment budgets. Storage of fine sediment with a high P content in river channels is, therefore, an important process influencing the resulting export from the catchment during extreme flow events together with instream processing of sediment and P (e.g., uptake of P in macrophyte biomass) that might remove both fine sediment and P from the stream system through weed cutting and following the removal of the dead plant biomass.

The net P input was highest during the wet year of 2006–2007 (36%) and lowest during the driest year of 2008–2009, showing the importance of fluvial hydraulic processes in determining sediment and particulate P transfer through the river continuum (Kronvang et al., 1997; Walling et al., 1998). The deposited P in stream channels may be flushed downstream by later extreme events (spates) in discharge. Extreme rainfall episodes may, therefore, contribute to excess P loads in catchments derived from a combination of excess bank erosion and the flushing downstream of P-enriched sediments, which might be a problem overlooked in previous scenarios on effects of climate change on P losses and impacts on eutrophication (Jeppesen et al., 2009). The importance for downstream recipients is stressed by the fact that >70% of the particulate P in bank sediment (as well as in riverborne sediment) can be considered bioavailable and therefore potentially contributes to eutrophication.

Overbank phosphorus deposition in riparian areas is another important process that may influence net P fluxes through catchments (Kronvang et al., 2007, 2009b). Reconnection of inundated riparian areas to the fluvial system is popular as a mitigation measure for lowering nutrient loads in many countries (Hoffmann and Baattrup-Pedersen, 2007; Moss and Monstadt, 2008; Hoffmann et al., 2009; Kronvang et al., 2009b). Changes in the magnitude of bank erosion and storage processes in fluvial systems as well as their impact on phosphorus losses are expected to occur during the coming decades, caused especially by climate change but also by catchment management involving restoration of streams and wetlands. Increasing flooding inundation risks associated with climate change may also cause a risk for remobilization of P from the soil P pool and from deposited P, depending on factors such as the iron/P ratio in soil and deposited sediments and the hydrology of the river and floodplain (Hoffmann et al., 2009).

Table 7. Gross and net P mobilization from bank erosion as compared to the export of total P in the River Odense catchment during three hydrological years (2006–2007, 2007–2008, and 2008–2009).

Phosphorus mobilization and transport	2006–2007	2007–2008	2008–2009
	tonnes P		
Gross P mobilization from bank erosion	16.5	13.8	14.2
Net P mobilization from bank erosion	5.6–6.3	3.6–4.2	2.4–3.4
Total P transport in River Odense at Kratholm station during hydrological years (Oct.–Sept.)	33.4	21.5	11.6
Contribution from bank erosion to total transport (%)	17–19	17–20	21–29
Total P loss from diffuse sources from the River Odense, Kratholm during hydrological years (Oct.–Sept.)	27.3	15.4	5.5
Contribution of bank erosion to diffuse losses (%)	21–23	23–27	44–62

The net input of P from bank erosion amounted on average to 18 to 25% of the annual total P export from the River Odense catchment but 22 to 53% of the annual total P loss from diffuse sources in the catchment (Table 7). Therefore, our study proves bank erosion to be a highly important diffuse P source in lowland river basins. Fingerprinting studies tracing the origin of suspended sediment in catchments has proven bank erosion to be an important source in some studies (Owens et al., 2000; Walling et al., 1998), whereas in other cases tile drains (Russell et al., 2001) or topsoils contribute more suspended sediment than eroding banks (Collins et al., 1997).

We have demonstrated that during all seasons a large part of the exported P with suspended sediment from the catchment is or can be bioavailable when transported to downstream surface water systems like an estuary as is the case in the River Odense. Bank erosion–derived P is therefore also important as an eutrophication driver in surface waters. Few P models working at catchment scale include bank erosion as a diffuse P source (Schoumans et al., 2009; Kronvang et al., 2009a). The controls on cohesive river bank erosion and fluvial processes of sedimentation and resuspension is therefore a fundamental problem when modeling P sources and dynamics within catchments.

An important mitigation measure that might reduce the problem of bank erosion as a diffuse P source is to change land use along the riparian corridor from intensive agricultural production to grassland or riparian forest as proven by Zaimes et al. (2008). This study confirms that planting trees in buffer strips reduces bank erosion by as much as 25 to 40% compared to erosion rates from buffer strips planted with vegetation such as grass and herbs. The high P content of bank material found in this study (718 mg P kg^{-1}) may be derived from different sources related to agricultural activities (fertilization), inflow of reduced groundwater, maintenance processes in the stream channel (weed cutting and dredging), and inflow of stream water through the hyporheic zone. Active mining of P in the buffer strip through phytoremediation can therefore be a very important maintenance activity (Adler et al., 2008).

In summary, we can conclude the following from our measurements in the River Odense catchment, Denmark: (i) bank erosion is an important diffuse P source in lowland river systems, delivering 21 to 62% of the annual export of total P from diffuse sources; (ii) the dominant part of P in suspended sediment collected at the catchment outlet was measured to be bioavailable (71.7%); (iii) bank erosion was measured to be significantly lower ($p < 0.05$) along buffer strips with high vegetation (natural trees and shrubs) than along buffer strips with low vegetation (grass and herbs) during all three study years; (iv) neither stream size nor stream disturbance (channelization) or width of an uncultivated buffer strip had any significant ($p < 0.05$) influence on bank erosion and P loss during each of the three study years.

The outcome of this study is important for catchment managers working with implementation of mitigation measures, such as buffer strips, for reducing P losses to surface waters and for catchment modelers who need to include the importance of bank erosion as a diffuse P source when analyzing P sources and P loadings.

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