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Quantification of ditch bank erosion in a drained forested catchment

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In boreal areas where forestry extends to drained peatlands, erosion and sediment transport from ditch networks are among the most harmful effects of forestry. To explore and quantify the initial bank erosion processes at their source area, topography of a 3.8-metre-long section of a newly cleaned ditch bank was measured at different times with a pin meter. The risk of erosion in the ditch bank was increased by generating elevated water table conditions using artificial irrigation. Erosion and soil deposition were estimated by calculating the changes in the bank topography between the sequential measurements. The total erosion was 41 kg m^{-1} within the studied stretch. The eroded material was deposited at the bottom of the ditch and exposed to transportation only later during greater discharge events. The pin meter was found to be a workable device for detecting the erosion-induced changes (1–15 cm) in the ditch dimensions.

Introduction

In Finland, large scale drainage of peatlands for forestry purposes started in the 1950s. Of the 8.7 million hectares of peatlands, 4.7 million hectares have been drained for forestry (Finnish Forest Research Institute 2013). Pristine peatlands are no longer claimed for forestry drainage, but the focus is on the maintenance of the existing ditch networks, such as ditch cleaning and complementary ditching. Depending on site properties, ditch cleaning is needed every 20–40 years after previous ditching because the ditches become shallower due to regrowth of vegetation and sedimentation of eroded soil material, thus reducing the water-conducting capacity of the ditches (Hökkä *et al*. 2000). In 2012, ditch network maintenance was carried out on 52 000 ha (Finnish Forest Research Institute 2013).

Ditch network maintenance (DNM) in peatland forests is the main contributor to sediment load to water courses from forestry areas (Finér *et al*. 2010). A comprehensive study covering 40 ditch maintenance areas by Joensuu *et al*. (2002) showed a significant increase in suspended solid concentrations in runoff water after the DNM activities. Their empirical model showed that the increase in sediment load was strongly related to the total length of the ditches cut into the fine textured mineral subsoil below peat. Thus,

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DNM does not necessarily increase sediment load much from areas where the ditches remain in the organic peat layer, particularly in unhumified peat. Where the ditches in initial ditching or DNM reach easily erodible mineral soil layers below peat, however, up to several thousands of kilograms of suspended solids can be exported to water courses within the first few years after the operation. An increase of 800 kg ha^{-1} a^{-1} in suspended solids load has been reported to occur after ditching (Ahtiainen and Huttunen 1999). Since nutrients, especially phosphorus, are transported either as structural components of soil particles or adsorbed to their surfaces, nutrient loads are clearly bound with sediment load (e.g. Marttila and Kløve 2010a). After the first years, the sediment load clearly decreases (Nieminen *et al.* 2010) and within ten years the concentrations mostly return back to the initial level (Joensuu *et al.* 2006). In areas with fine-textured mineral subsoils, such as clay, the load may never return to the pre-maintenance level (Joensuu *et al.* 2012). In the national scale in Finland, DNM is estimated to increase the annual suspended solid load by 54% as compared with the natural background load from forested areas (Finér *et al.* 2010).

The problems followed by erosion and high sediment load include siltation, turbidity, and decreased water depths in the downstream waterways. Sediment load can also have negative effects on the aquatic biota, such as reducing primary production and decreasing the quality of spawning grounds for fish (Bilotta and Brazier 2008). Sediment and associated nutrient loads enhance eutrophication of water bodies. The effects of ditching and ditch network maintenance on sediment concentrations in ditch water and sediment loads leaving the drained area, as well as the duration of the ditching impact, have been studied extensively (Lundin and Bergquist 1990, Ahtiainen and Huttunen 1999, Joensuu *et al.* 2002, Marttila and Kløve 2010b, Nieminen *et al.* 2010). In these earlier studies, the main focus was on the quality of water outflow and load from the drainage area to the receiving water courses, and the mechanisms inside the catchments have not been fully assessed and quantified. By understanding and quantifying the processes behind erosion and sediment transport from forest ditches, better water protection methods could be developed and implemented.

Erosion of mineral soil has been extensively studied (e.g. Morgan 2005). The erosion process consists of detachment and transport of soil particles from their original location. Soil type, the intensity of erosive force (water or wind), land slope and vegetation cover are among the factors controlling erosion processes. Bank stability is affected by bank slope geometry, seepage and tension cracks (Hemphill and Bramley 1989). The role of seepage on bank erosion has been reviewed by Fox and Wilson (2010) who stated that the mechanisms include direct erosion by seepage or pipe flow and indirect effects caused by changes in soil pore water pressure and seepage gradient.

Erosion and sediment transport from cleaned ditches occur by several interacting processes and mechanisms (Marttila and Kløve 2010b). Erosion can be caused by flowing water and sheet wash while the bottom of ditches can suffer from aggradation and degradation. Undermining of the ditch banks can lead to bank collapse. Eroded and transported soil material can be temporarily deposited along the way to be re-suspended later with greater discharges. Previous studies indicate that the risk for erosion is greatest from the ditches cut into the fine-textured mineral soil and during the first year after DNM (Joensuu *et al.* 2002, Lappalainen *et al.* 2010). Previous data also indicate that erosion from ditch bottom is not sufficient to account for the total export of sediments from DNM areas, but the ditch banks may be a more important source due to their larger exposed area compared with the area of the ditch bottom. Silver and Joensuu (2005) studied the deterioration of cleaned ditches and found that it was the fastest in the ditches with fine-textured mineral subsoil, the main contributing mechanism being the bank collapse caused by frost heaving.

While sediment transport at the ditch outlet of drained peatland catchments was measured in many studies using flow and sediment concentration observations (Joensuu *et al.* 2002, Marttila and Kløve 2010b), the actual erosion processes in the ditch networks of drained peatlands are rarely monitored. The options for measuring erosion in terms of changing ditch dimensions include two dimensional profile measurements and three dimensional measurements. Jester and Klik (2005) compared measurements of surface microtopography for assessing surface roughness and studied the use of contact devices (roller chain, pin meter) and non-contact devices (laser scanning, stereophotographs). Jester and Klik (2005) noted that the laser scanning method provided the highest precision and spatial resolution, whereas contact devices had limited resolution power but produced data that are ready for further analysis. A pin meter device has recently been applied to measure soil erosion and deposition (Ferrick and Gatto 2005, Kornecki *et al*. 2008) and soil surface roughness (García Moreno *et al*. 2008, Vidal Vázquez *et al*. 2010).

The aim of this work was to study soil erosion processes in ditch banks right after DNM operation in a fine-textured mineral soil, i.e., in a situation where the risk for erosion is particularly high. Local erosion risk is experimentally increased by generating elevated water table using irrigation at the top of the ditch bank. Also discussed are the importance of ditch banks as source areas of sediment load into water courses and the sensitivity of the chosen methodology for studying erosion processes. Two main hypotheses presented for the study are: (1) a considerable amount of sediment load originates from ditch banks, and (2) seepage plays a role in the erosion process of a forest ditch. Erosion was measured in terms of evolving ditch sidewall dimensions by using a pin meter with light-weight aluminium pins. A specific aim was to test the applicability of the measurement system in the field conditions and assess the suitability and accuracy of the method for detecting ditch erosion.

Material and methods

The experimental site and setup

The field experiment was conducted in a drained peatland area located in Karkkila municipality in southern Finland (60°34´N, 24°22´E). The mean annual air temperature in the region is about 4 °C, with means of –6 °C in February and 16 °C in July. Average annual precipitation is 650–700 mm, with about 20%–40% falling as snow. The peatland area was classified as a *Vaccinium myrtillus* type site (Vasander and Laine 2008), and it was covered by a mature forest stand dominated by Norway spruce (*Picea abies*) with varying mixture of Scots pine (*Pinus sylvestris*) and downy birch (*Betula pubescens*). The stand volume was 280 m^3 ha^{-1}. The peatland area was drained for the first time in 1939, manually with shovels. In 1967, DNM was carried out by cleaning the ditches and by digging new ones with excavators to produce an average ditch spacing of 30–40 m. In the autumn of 2010, the ditches were cleaned for the second time and a few complementary ditches were excavated. On average, the width of the cleaned ditches was 0.3 m at the bottom, 2 m at the top, and the depth of the ditches was 1 m. Our experiment was carried out along one of the ditches in the area (Fig. 1), and that ditch was cleaned on 19 October 2010, shortly before winter freezing started.

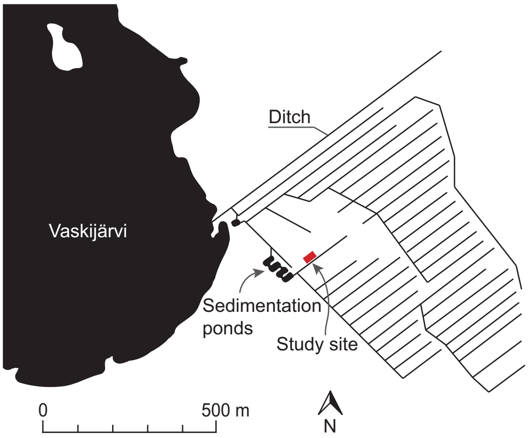

Fig. 1. The area of ditch network maintenance and the study site in Santamäensuo, Karkkila, southern Finland.

To study the bank erosion in ditches dug into fine-textured mineral soil, the location of our experimental ditch was in an area with a nearly non-existent peat layer (5–10 cm, including the litter layer) and fully exposed sandy loam ditch banks. The experimental ditch was a feeder ditch rather than a main outflow ditch, where major flow depth variations could have interfered with the measurements. The dimensions of the ditch were: depth 0.8–1 m, width at the level of the soil surface 2 m, width at the bottom 0.3 m, and mean slope of the bank 38°.

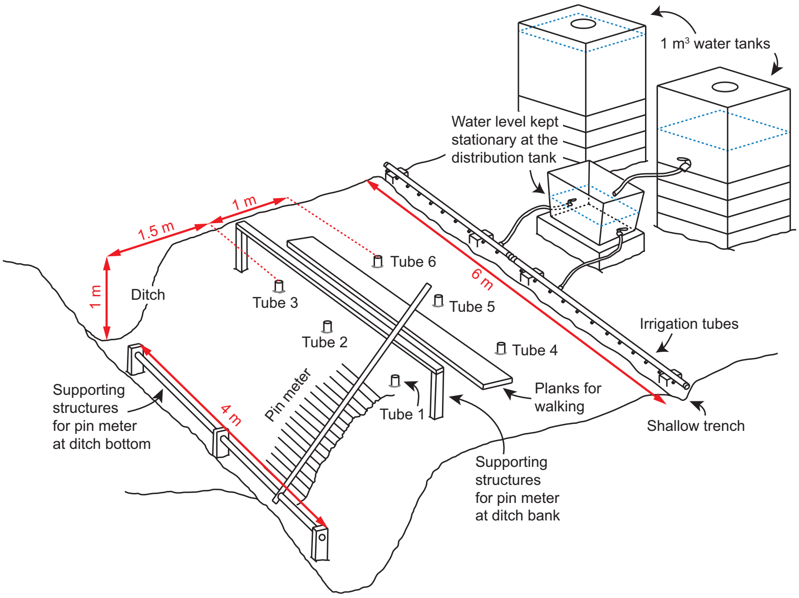

Fig. 2. The setup of the field experiment showing the irrigation system, the locations of the groundwater tubes 1–6 and the structures for pin meter measurements.

We used the pin meter method (e.g. Ferrick and Gatto 2005, García Moreno *et al*. 2008, Kornecki *et al*. 2008, Vidal Vázquez *et al*. 2010) and artificial irrigation to study seepage-induced erosion processes in the bank of the experimental ditch (Figs. 2–3). The pin meter was presumed to provide reliable data in field conditions from successive measurement campaigns at the same site. The irrigation was applied to increase seepage-induced erosion risk right after ditch cleaning and to speed up the erosion process. The soil material that was excavated, was in most cases piled next to the side of the ditch. For the experimental site of this study, the piling was not conducted to allow the construction of the irrigation and erosion measurement systems and to avoid any erosion from the soil piles.

The studied bank of the experimental ditch was 3.8 metres long in the direction of the ditch, and one side was instrumented. The site was instrumented as soon as the experimental ditch was cleaned. The experimental setup (Fig. 2) consisted of a line type irrigation system, groundwater tubes, and appropriate structures for measuring ditch bank microtopography with a pin meter (Fig. 3). The line irrigation system (Fig. 2) consisted of two 1 m^3 water tanks that were filled with water pumped from the nearby sedimentation pond. From these tanks, water was conveyed to a smaller distribution tank, where it was diverted to the irrigation tubes purging water into the forest floor. The water level in the distribution tank was kept at a constant level to produce a stationary flow. The tubes spread water into a 6 metre long, shallow trench that was excavated for this purpose. Six perforated groundwater tubes were installed to monitor the changes in the groundwater level between the ditch bank and the irrigation system. Three of the tubes were located 150 cm and the other three 250 cm from the centre of the experimental ditch (Fig. 2). The groundwater levels were recorded using TruTrack water height sensors (WT-HR, 1 m) at 1-minute intervals. The TruTrack sensors (WT-HR, 25 cm) were also used to monitor the water level in the ditch bottom upstream and downstream from the studied ditch bank.

The pin meter was placed on supporting structures (Fig. 2). The upper supporting structure was made from a 4-m-long plank resting on columns driven vertically deep into the ground. The lower supporting structure consisted of two metal pipes supported again by wooden columns driven deep into the ditch bottom soil. The vertical and horizontal positions of the supporting structures were checked at the start and end of the measurement period. As the pin meter was laying on the supports, the light-weight aluminium pins were carefully lowered to barely touch the soil surface and not to cause disturbance of the soil surface. Then the pins were locked and the pin meter was moved for taking a photograph against a dark brown background sheet (thick plywood), which was placed nearby. The background sheet was marked with scales, from which the elevation of each pin could be determined. The pin meter was photographed using the zoom feature of a digital camera to reduce lens distortion, which can cause an error in the positioned values.

Irrigation was repeated three times (on 1, 2 and 4 Nov.), and the pin meter measurements were conducted five times (on 28–29 Oct., and 2, 4, 9 and 16 Nov.) to produce an estimate of the bank topography covering the 4-m-long stretch of the ditch bank. The purpose of the first measurement (M1) was to determine the initial bank topography. The second (M2) and third (M3) measurements were carried out shortly before and during the second and third irrigation, respectively, and the fourth (M4) measurement was taken 5 days and the fifth (M5) 12 days after the third irrigation. The amount of water applied was 2.6 m^3 in the first irrigation that continued for 3.6 h, and 3.8 m^3 in the second and third irrigations that continued for 4.3 and 4.8 h, respectively. No surface runoff was observed during the irrigations, and all water infiltrated into the soil. After the third irrigation on 8 November the air temperature dropped below zero and the bank surface was frozen; but then it melted, which enabled us, although not planned in advance, to compare ditch bank erosion under frozen (M4) and unfrozen soil-bank conditions (M5) at the end of the study period. After the last measurement (M5), the temperatures dropped constantly below zero and the site became covered with snow.

Data processing

Because of the distortion caused by the camera lens and the angle of the camera in relation to the pin meter, the photographs were first rectified using Adobe Photoshop®. Then the photographs were digitized with an open source software called Engauge Digitizer (http://digitizer.sourceforge.net/) to produce numerical values for the pin positions. A validation photograph of the pin meter (including a few pins at known positions) was taken when the camera was attached to its stand. These photographs were used to validate the rectification.

The pins of the pin meter were located 2 cm apart from each other and the measurement positions along the direction of the ditch were at 10 or 20 cm intervals. The number of measurement positions was 22 for measurement M1, 39 for M2, 35 for M3, 39 for M4, and 20 for M5. The number and location of pin meter positions varied between measurement sets because the time required for one pin meter measurement varied according to occasional malfunction of the pin meter and because the objective was to focus the measurements on the bank areas with the greatest visually detectable elevation changes. Thus the densities of the measurement points were different in the two different directions and among the different measurements (M1–M5). For each measurement (M1–M5), however, the data were interpolated over the whole measurement area with ordinary kriging using a grid size of 2 cm × 2 cm. Ordinary kriging was applied within the R environment using the predict-function in the *gstat* package (Pebesma 2004). Variogram was assumed to be linear with the anisotropy parameters having values of 90 (main axis direction of the anisotropy ellipse) and 0.6–0.7 (the anisotropy ratio). The data were processed by rotating the coordinate system (38°) in such a way that the z-axis (the value for soil surface elevation) was perpendicular to the ditch bank.

The sensitivity of the elevation estimates to the measurement density was studied by using the measurement M2 and subsets of the M2 data. The sensitivity was studied by leaving a share of the M2 measurements out of the calculations, deriving the elevation surface using the kriging procedure, and comparing the estimated elevation surface with the results produced earlier using all measurements. First, every other pin meter measurement position in the x-direction (direction of the ditch) was systematically omitted from the data, doubling the pin meter distance from the original 10 cm to 20 cm. Second, we tested how progressive removal of measurement points in the y-direction affected the results. The data in the y-direction were dense enough to study the sensitivity of elevation estimates to 2 cm (the original distance between pins), 4 cm, 8 cm, and 16 cm pin distances.

The interpolated grid surfaces that were produced with kriging for each measurement (M1–M5) were compared with each other to illustrate the temporal variation in the bank surface elevation. It was assumed that the changes in elevation during the frost-free period were mainly caused by erosion and deposition, and other soil deformations, such as swelling and shrinking, were assumed to have little impact on the elevation of mineral soil ditch bank. Later in the text, decreased surface elevation is thus referred to as "erosion" and increased elevation to as "deposition". The differences in the bank surface were described with cumulative empirical probability distributions. All of the N numbers of elevation differences were arranged in ascending order, and the empirical probability (p_n) for each difference was calculated based on the position (n) of that difference

$$p_n = (n - 0.5)/N \tag{1}$$

and the cumulative probability (P_n) of nth position was calculated as

$$P_n = \sum_{k \le n} p_k \tag{2}$$

Cumulative empirical probability distributions were then formed by plotting the cumulative probabilities against the elevation differences.

The physical properties of the soil were determined from soil samples taken from the ditch bank and bottom. A total of nine volumetric soil samples (400 cm^3) were taken from different locations and heights of the bank and analyzed for bulk density and organic matter content. The average bulk density was 1240 kg m^{-3} (SD = 230 kg m^{-3}) and the average organic matter content was 5.1% (SD = 3.8%). The mass for the eroded and deposited soil volumes were calculated by using the bulk densities derived from these soil samples. Based on additional soil samples taken from ditch bank (nine samples) and their particle size distribution, the bank soil type was sandy loam according to the USDA classification system (e.g. USDA 1987). The soil samples from the ditch bottom indicated that the soil type at the ditch bottom was loamy sand.

Results

Hydrometeorological conditions during the experiment

At the Ahmoolammi weather station, located 4 km from the site (Kotamäki *et al*. 2009), the air temperature (15 minute measurement frequency) during the experiment varied between –8 °C and +7 °C, and there was a clear frost period between 6 and 10 November (Fig. 4). Soil was initially relatively wet before the experiment and there were rainfall events during the experiment. The experiment was finished when the site became snow-covered and the air temperature dropped constantly below 0 °C after 17 November. The total amount of water irrigated along the experimental ditch was 1700 dm^3 m^{-1} and the maximum intensity of irrigation was 162 dm^3 m^{-1} h^{-1} (Fig. 4). Between M1 and M5, precipitation was 43 mm.

The groundwater level responded rapidly to irrigation as well as to the rainfall events (Fig. 5). During the irrigations, the hydraulic gradient varied from 0.09 to 0.52 m m^{-1} between the groundwater level in tubes 1–3 and the water level in the ditch, which led to a formation of a seepage face in the ditch bank. The seepage face was visually observed in the middle parts of the ditch bank during the experiment. The groundwater level did not rise up to the soil surface but was at maximum about 6 cm below the soil surface (tubes 2 and 3). The rainfall events clearly slowed down the lowering of the groundwater level after the second irrigation. The groundwater responded similarly in the three replicate tubes along the ditch in both tube lines (1–3 and 4–6). During the final irrigation period (lasting 4.8 hours), the groundwater level in the upper tubes (4–6) reached a steady-state condition within 3 hours, while the groundwater level in the lower tubes (1–3) was still rising until the irrigation was stopped. The water level in the ditch varied between 10 and 15 cm (Fig. 5).

Changes in ditch bank topography

The changes in the ditch bank topography (Fig. 6), i.e. the changes in the soil surface eleva-

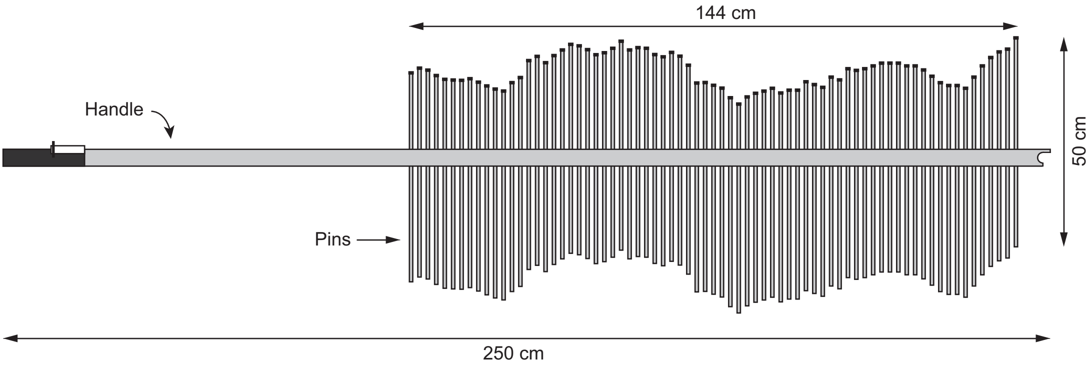

Fig. 3. The pin meter used in the study. The material is aluminium.

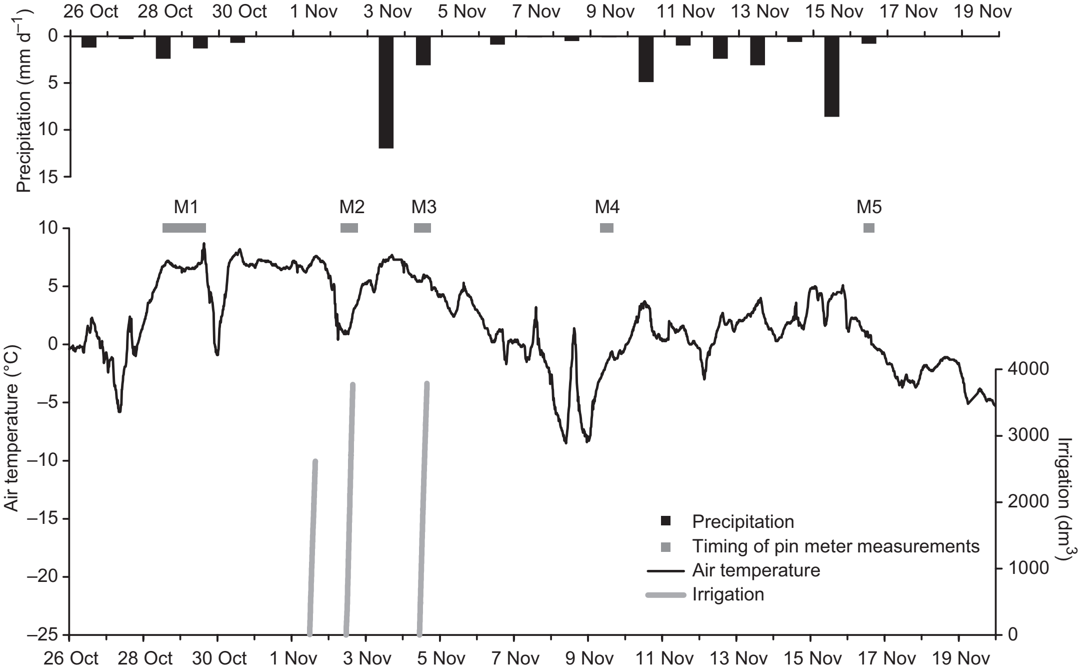

Fig. 4. Daily precipitation, daily air temperature, volume of irrigation water, and timing of the pin meter measurements (M1–M5) during the study period. Precipitation and air temperature data were provided by SoilWeather network/MTT Agrifood Research Finland & Finnish Environment Institute.

tion, are visualized by showing the difference between the elevations in the measurements M2–M5 and the initial elevation (M1). After the first irrigation (Fig. 6a), there was a systematic accumulation of soil material (the red-coloured areas) to the bottom of the ditch bank, but the erosion of the bank material (the green-coloured areas) was not systematically concentrated in any specific area. The maximum increase in the elevation averaged along the ditch direction (x-axis) was 2.8 cm from M1 to M2 and occurred at about 18 cm from the ditch bottom (plotted as a function of y in Fig. 6). The mean absolute difference in the elevation was 1.18 cm between M1 and M2.

After the second irrigation (Fig. 6b), the same trend continued and the maximum increase in the elevation averaged along the ditch direction (x-axis) was 3.9 cm. In the right-hand side of the ditch bank shown in Fig. 6b, however, soil erosion and deposition were greater than in the other parts

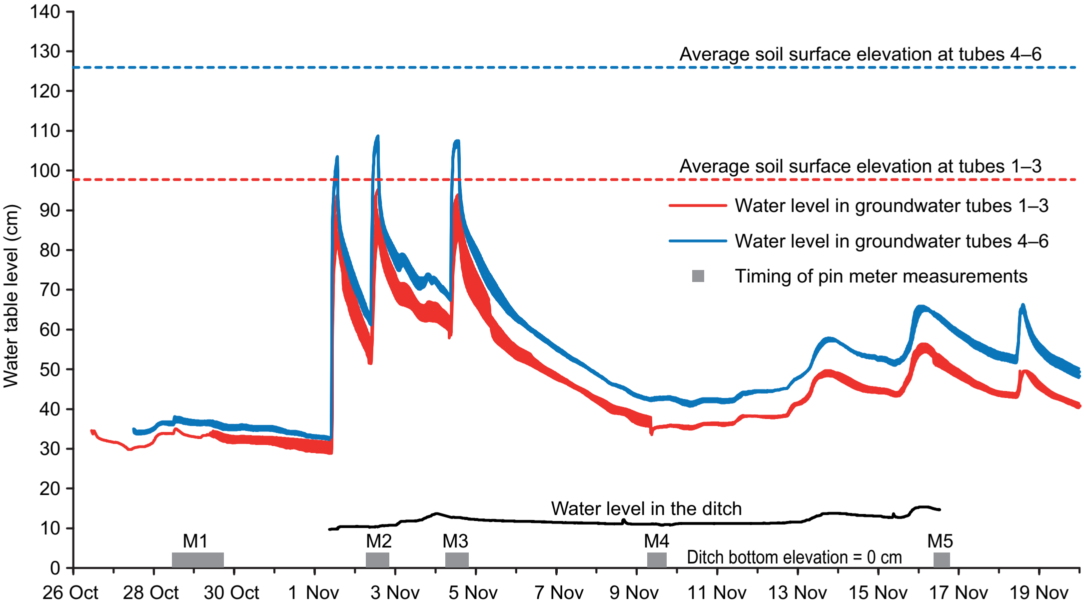

Fig. 5. Variations of the groundwater level in the soil (mean for tubes 1–3 and tubes 4–6, *see* Fig. 2) and the ditch water level in relation to the ditch bottom. The average soil surface elevation at the groundwater tube locations (tubes 1–3 and tubes 4–6) and the timing of the pin meter measurements (M1–M5) are also shown.

of the ditch bank. The mean absolute difference in elevation was 2.07 cm between M3 and M1 and 1.56 cm between M3 and M2. The absolute elevation change between M3 and M2 (1.56 cm) was clearly higher than that between M2 and M1 (1.18 cm). The average groundwater level was evidently higher between M2 and M3 than between M1 and M2.

The measurement M4 (Fig. 6c) was made during frost heave. In many parts of the ditch bank, frost heave formed small soil/ice columns that peaked a few centimetres from the soil surface. This was observed in the field and can also be seen in Fig. 6c, which shows that the soil/ice surface is clearly higher than that in other measurements in many parts of the ditch bank, especially in the middle parts. The last measurement (M5) (Fig. 6d) was made when the frost had melted and the soil surface appeared to have returned to the level before the frost heave. The absolute elevation change between M5 and M3 (1.03 cm) was smaller than the changes caused by irrigations.

The differences in ditch bank topography in different bank sections (upper, middle, lower in Fig. 6) as compared with that at the initial stage (M1) were also quantified with the cumulative empirical probability distributions (Fig. 7). In the upper section (Fig. 7a), the differences indicate erosion on 77% of the surface area between M1 and M2. The situation remained almost the same until the last measurement (M5), except that there was a large temporary change in elevation due to the frost heaving (M1–M4). When the frost melted, the ditch bank elevation returned to the pre-frost situation.

In the middle section of the measurement area (Fig. 7b), the difference in the ditch bank topography between the first (M1) and second (M2) measurements was greater than in the upper section (Fig. 7a). The cumulative probability distribution in Fig. 7b indicates that in 70% of the area there was erosion and in 30% of the area there was deposition. Most of the erosion in the middle section took place between the second (M2) and third (M3) measurements. Similar to the upper section (Fig. 7a), the frost heave temporarily increased the elevation (M4 as compared with M1), which returned back to the initial stage when the frost melted (M5). The percentage of the surface area that had eroded between M1 and M5 was 74% (Fig. 7b).

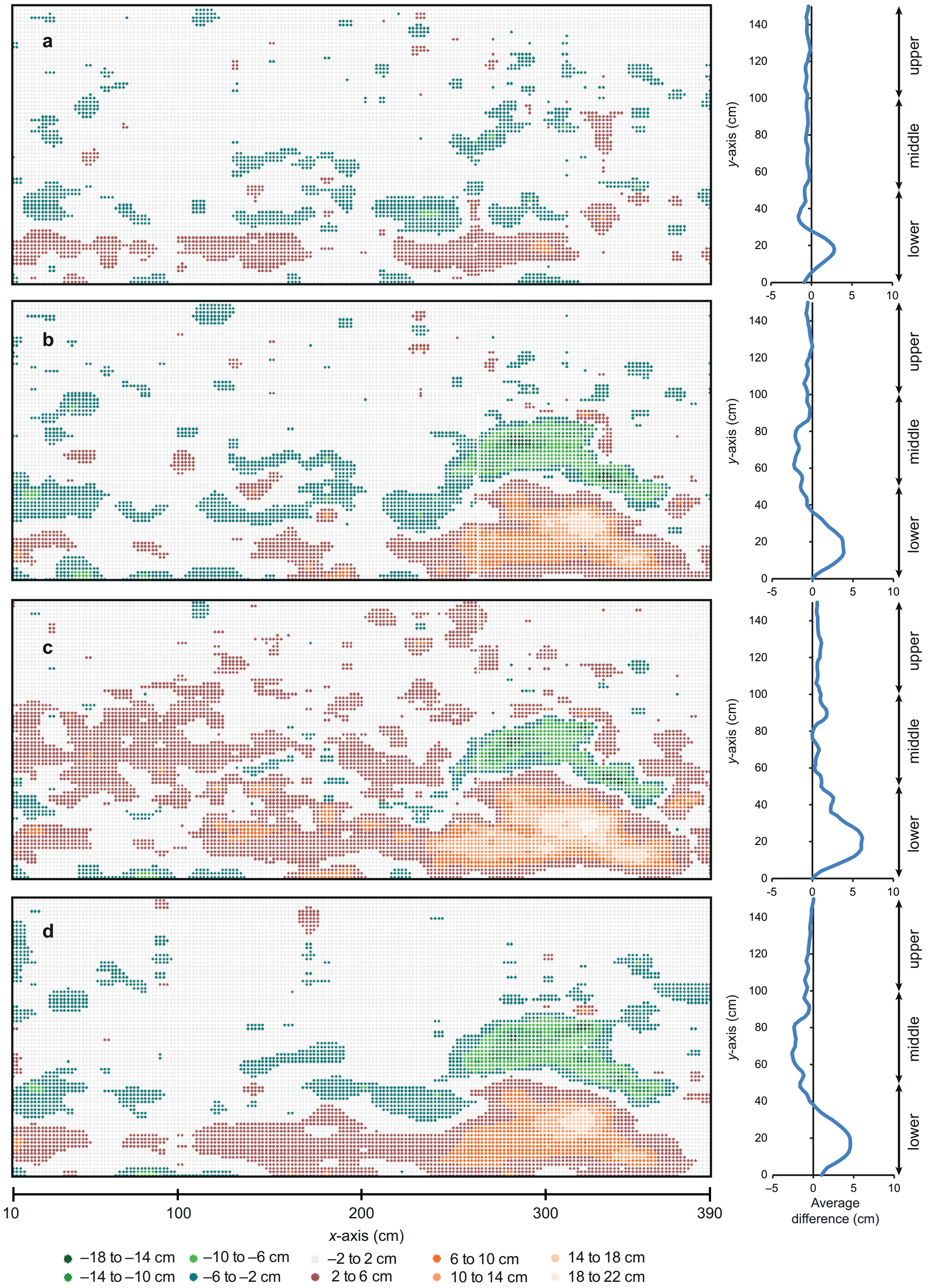

Fig. 6. Differences in the ditch bank topography (*z*-axis) between the measurements (**a**) M2 and M1, (**b**) M3 and M1, (**c**) M4 and M1 (frost heave), and (**d**) M5 and M1. Topography is viewed at a 38° angle, with the *z*-axis perpendicular to the ditch bank. In the right-hand side graphs, the average elevation differences are drawn as the function of the distance along the ditch bank (*y*-axis perpendicular to the *x*-axis). The subdivision of the ditch bank into the different sections is also shown.

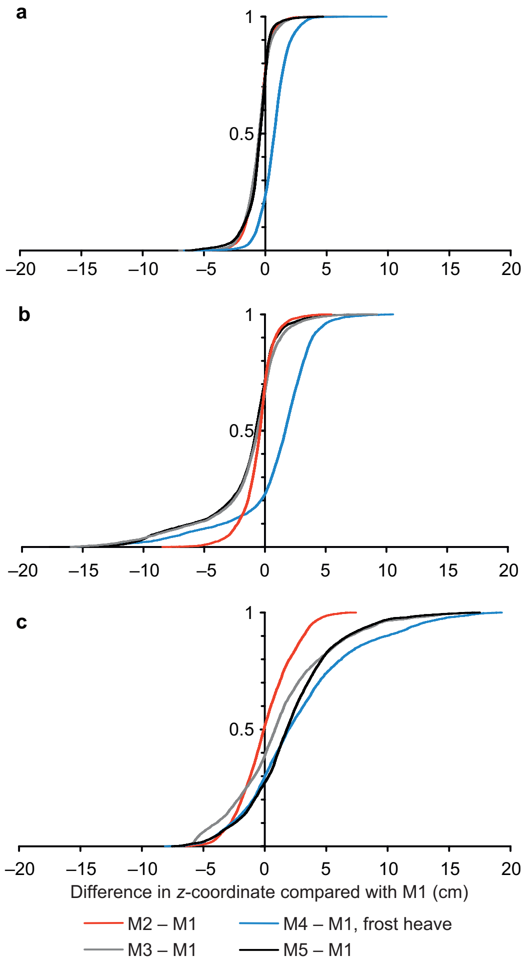

Fig. 7. Empirical probability distributions of the changes in ditch bank topography in (**a**) upper, (**b**) middle and (**c**) lower sections of the measurement area (*see* Fig. 6) at different measurement times (M2, M3, M4 and M5) compared to the first measurement (M1).

In contrast to the upper and middle sections, the lower section (Fig. 7c) showed clear deposition of soil material. Most of the deposition occurred between the second (M2) and the third (M3) measurements. The frost heave increased the elevation (M4 – M1 in Fig. 7c), but contrary to the upper and middle sections, the situation did not return to the initial elevation after the frost melted. The cumulative probability distribution shifted to the right, indicating more deposition than erosion. The last measurement (M5 – M1) showed that deposition eventually occurred on 69% of the surface area in the lower section.

According to the results, soil erosion and deposition were minor in the upper section of the ditch bank. The middle section contributed most to the soil erosion, and the eroded material was deposited in the lower section of the ditch bank. Frost heave had a clear effect on all sections of the bank: frost lifted the surface a few centimetres, but the change was temporary.

Sensitivity to measurement density

The sensitivity analysis to assess the effect of varying measurement density in the x-direction (density of pin measurements along the ditch) and the y-direction (density of pin measurements along the bank) on elevation estimates revealed that the elevation estimates were most sensitive to pin density in the y-direction (Fig. 8). Decreasing the pin density in the x-direction from 10 cm to 20 cm caused less error than decreasing the density in the y-direction from 8 cm to 16 cm. When the differences caused by sampling subsets of the data are compared against the elevation changes in different bank sections (*see* Fig. 7), the elevation changes in the upper section of the ditch bank (except for M4) appear to fall within the error caused by varying the measurement density. However, the elevation changes in the middle and lower sections are clearly greater than the error introduced by varying the measurement density, except for the 16 cm pin density in the y-direction, which indicated significantly larger error than the other sensitivity analyses. The mean absolute difference (M2 – M1) was 1.18 cm when using all available data. By removing data in the x-direction (every other measurements removed), the mean absolute difference was 1.43 cm. The removal of data in the y-direction resulted in mean absolute differences of 1.21 cm for the 4 cm pin density, 1.32 cm for the 6 cm pin density, and 1.91 cm for the 16 cm pin density. As a result of data removal in the x-direction, 90% of the values differed less than 1.8 cm from the initial data, and as a result of data removal in the y-direction 90% of values differed less than 0.7 cm, 1.5 cm, and 3.3 cm for the 4, 8, and 16 cm pin densities, respectively.

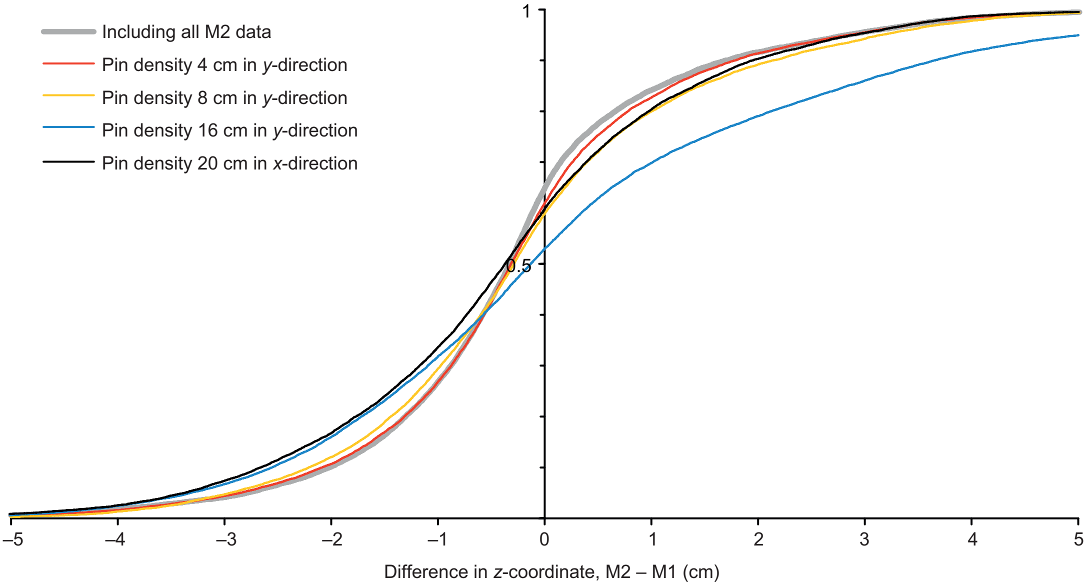

Fig. 8. Empirical probability distributions of the first pin meter measurement (M1) compared to the second measurement (M2), using different shares of the M2 data to evaluate the sensitivity of the data to the results. The initial pin density was 10 cm in the *x*-direction and 2 cm in the *y*-direction.

Volume changes and mass balances of the ditch bank

The changes in the ditch bank topography were converted into soil volumes (dm^3 m^{-1}) and mass balances per one meter of ditch (kg m^{-1}) for each section of the bank (upper, middle and lower; Fig. 6) assuming that the same amount of soil eroded from both sides of the ditch. In the upper section, the largest changes took place between the measurements M1 and M2. There was 6.9 kg m^{-1} (6.8 dm^3 m^{-1}) of soil material eroded and the amount deposited was 1.4 kg m^{-1} (1.4 dm^3 m^{-1}). Comparing the end of the measurement period with the initial stage (M1 – M5) the total eroded mass was estimated to be 6.7 kg m^{-1} (6.5 dm^3 m^{-1}) and the deposited mass was 1.3 kg m^{-1} (1.2 dm^3 m^{-1}). Thus the balance indicates that 5.4 kg m^{-1} of soil was lost from the upper section of the bank during the study.

The middle section was the area where most of the erosion took place. Between M1 and M2 9.9 kg m^{-1} (7.5 dm^3 m^{-1}) of soil was eroded, by measurement M3 the eroded mass had increased to 23.8 kg m^{-1} (17.6 dm^3 m^{-1}). The last measurement indicated that total of 25.7 kg m^{-1} (18.9 dm^3 m^{-1}) was eroded while 2.4 kg m^{-1} (1.8 dm^3 m^{-1}) was deposited. Mass balance suggests that 23.3 kg m^{-1} of soil was lost from the middle section.

Most of the material eroded from the upper section was deposited in the lower section. Between M1 and M2, 13.9 kg m^{-1} (10.3 dm^3 m^{-1}) of the soil was deposited and the amount eroded was almost the same, 10.9 kg m^{-1} (7.9 dm^3 m^{-1}). In the measurement M3, 34.3 kg m^{-1} (24.6 dm^3 m^{-1}) of soil deposition was found, but the amount eroded did not change from the previous measurement. Thereafter, the deposition increased even more, and at M5 the total amount of deposited material was 38.4 kg m^{-1} (27.6 dm^3 m^{-1}) and that of eroded material, 9.0 kg m^{-1} (6.8 dm^3 m^{-1}). Thus the lower section gained 29.4 kg m^{-1} of the soil during the study.

The overall balance between erosion and deposition in the ditch bank was 0.7 kg m^{-1} in favour of deposition. This indicates that during the experiment, the eroded soil was not carried further down along the ditch bottom but was deposited in the lower bank section near the ditch bottom to be potentially transported away with greater discharges.

The total amount of erosion in the whole measurement area during the study was 41.4 kg m^{-1}. Typical ditch spacing in thin peated areas is 50 m (Päivänen and Hånell 2012), totalling 200 m of ditches per hectare. Using these estimates, the amount of eroded soil was 8300 kg ha^{-1} during the study period of 19 days.

Discussion

Representativeness of the experimental site

The experimental site was situated within a drained spruce swamp forest. There are 2.1 million ha of spruce peatlands in Finland which is 24% of the total peatland area (Finnish Forest Research Institute 2013). According to the Finnish National Forest Inventory (years 1986–1994) 66% of the spruce peatlands are drained and 46% of the drained spruce peatlands are shallow peated with peat layer thickness less than 0.3 m (Hökkä *et al*. 2002). Of the total drained peatland area 27% are shallow peated (Hökkä *et al*. 2002). There is less data available on the variety of subsoil type on drained peatland areas. A rough estimate of the amount of drained peatlands with fine textured mineral subsoil can be drawn from a study where 40 DNM sites were surveyed (Joensuu *et al*. 2002) and about one third of the sites had fine textured mineral subsoil (Joensuu *et al*. 2001).

We visited a few possible DNM sites before deciding on this one. The aim was to choose a site with high erosion risk. Thus a shallow peated site with fine textured mineral subsoil was chosen. There was a mature tree stand on the site. Typically it would have been cut before DNM but this was not the case in our study site. Thus, evapotranspiration by the tree stand has an effect on the hydrology of our study site. However, the experiment was short and made in late autumn when evapotranspiration was low. The shovel that was used in the DNM work had a standard shape that is generally used in DNM in Finland. Thus the shape of the studied ditch cross-section can be regarded to be typical.

Artificial irrigation was applied to generate a high risk of seepage erosion in the field experiment. The role of other erosion processes, such as raindrop and flowing water impacts and other bank deformation processes, was assumed to be less important than the seepage erosion induced by the irrigation in the studied feeder ditch. Another option besides irrigation experiment would have been to build a control site in another feeder ditch where no irrigation would have been applied. Such experimental design would have revealed the role of irrigation-induced seepage erosion in comparison to non-irrigation conditions. However, our study objective was not to explore irrigation impact on erosion as such but to explore ditch bank erosion at its source area under conditions of high erosion risk determined by the presence of both erodible soil material and extreme hydrological conditions (induced by irrigation).

Mechanisms of ditch bank erosion

To our knowledge, this is the first study that aimed to assess and quantify the source of suspended sediment load from a ditch-cleaned peatland drainage area. Previous studies (e.g. Joensuu *et al*. 2002, Marttila and Kløve 2010b) have reported the catchment-scale export loads to receiving water courses, but the sources and mechanisms behind the enhanced export have not been fully identified and quantified. In this study, we discovered that ditch bank erosion was an important mechanism when fine textured mineral subsoil was exposed at DNM. The ditch bank erosion estimate obtained in this study for the 19 days long study period (8300 kg ha^{-1}) characterises conditions of high erosion risk and is clearly higher than the suspended solids loads reported for ditching. Sallantaus (1986) estimated that in the research by Hynninen and Sepponen (1983) the initial ditching of a shallow-peated peatland with mineral subsoil increased sediment loading by 1500 kg ha^{-1} a^{-1} during the first three years. Ahtiainen and Huttunen (1999) reported an increase of 800 kg ha^{-1} a^{-1} during the first three years after ditching. These are the highest sediment loads reported in Finland, but still significantly lower than our estimate. The obvious reason for high erosion here was the fact that the bank erosion was enhanced by artificial irrigation. Another reason behind the difference between our estimate and the previously reported erosion loads is the variable peat layer thickness in the drainage areas. Not all the ditches in the drainage area have exposed mineral soil with increased erosion risk in the ditch bottom. The comparison also suggests that all the material eroded from the ditch bank is not necessarily transported further along the ditch network, or at least not as far as the water quality monitoring station in the catchment outlet. It should also be noted that our erosion estimate (8300 kg ha^{-1}) is not intended to represent a catchment-scale average load from all DNM areas, not even from a DNM area with considerably high erosion. The estimate represents the amount of potential local seepage-induced erosion that could occur from a ditch bank of a stretch of feeder ditch if all factors were in favour of seepage-erosion: the ditch was recently cleaned, the ditch was cut into erosion sensitive soil, and the water table level was high.

The meteorological conditions during and soon after DNM play a large role in the initial bank erosion processes. The sediment loads from drained peatlands are the highest during the actual ditching operation and then later during high snow-melt spring flows and summer storm flows (Joensuu *et al*. 1999, Marttila and Kløve 2010b). It is thus possible that the eroded ditch bank materials, particularly in the smaller feeder ditches as in this study, are not exported from the ditching areas until particularly high snow-melt or summer storm flows result in high water levels and discharges in all ditches. This assumption is also supported by the fact that the mass balance in this study was slightly in favour of deposition and thus the eroded material was only moved within the study area. A reasonable discharge is needed to move the eroded sediment further but such flow conditions did not occur during the study period. With a longer study period in snow-free conditions, there probably would have been more net erosion and it would have revealed how erosion processes continued after the initial deformation of the bank. The maximum amount of irrigation applied during one day was 3.8 m^3, giving a much higher water input than could be realised via precipitation at the exact location of the irrigation line. The amount of irrigation can be reflected against precipitation, when we estimate the upslope catchment area above the experimental site as 6 m (the length of the irrigation trench) by 35 m (half of the ditch spacing at the site). The rainfall depth of 18 mm falling on this catchment would correspond to the irrigation volume of 3.8 m^3. Daily precipitation data from the nearest weather station operated by the Finnish Meteorological Institute (Vihti Maasoja at the distance of 16 km) indicates that 18 mm d^{-1} or higher daily precipitation has a return period of 94 days, which illustrates how our irrigation volumes compare with the local natural precipitation. It should be noted that the objective of irrigation was not to simulate actual precipitation conditions, but to raise the water table near the soil surface and generate conditions of high erosion risk in a recently cleaned feeder ditch.

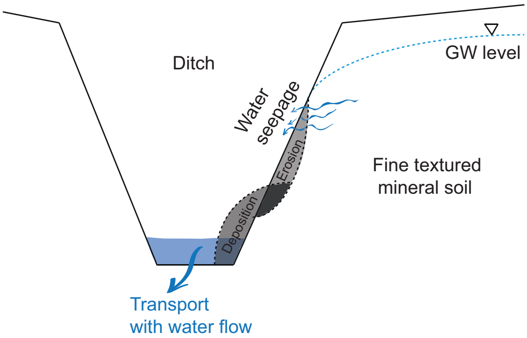

Fig. 9. Conceptualisation of the erosion and deposition processes in a ditch bank.

This study outlines a conceptualisation where bank erosion occurs in the area of seepage face and the material is eroded due to different mechanisms (e.g. seepage, gravitational forces, and freeze-thaw processes) and deposited to the bottom of the ditch and the lower parts of the ditch bank (Fig. 9). Because most of the erosion took place during the time when groundwater levels were highest, the main mechanism causing bank erosion was plausibly the seepage and wetting-induced loosening of the soil material. Similar findings have been reported by Howard and McLane (1988), who studied the erosion of a sand slope in an experimental chamber. Overland flow on soil surface can also cause erosion but this was not the case in our study since no overland flow was observed even during irrigation, but all added water percolated through soil. In our study, erosion by raindrops must have been negligible, since that would have affected the whole ditch bank similarly, but the erosion in the upper section (12.7 kg) was clearly smaller than the erosion in the area of seepage face in the middle section (48.8 kg). On the other hand, as the experimental ditch was not isolated from the surroundings, it is possible that the deposition results were not only influenced by the seepage-induced soil erosion from the studied ditch bank, but also by soil erosion from the opposite bank and the upstream part of the experimental ditch to the bottom of the ditch. However, the total deposition at the end of the study period was only 1.3 kg more than the erosion, thus indicating that our results were not much influenced by soil material outside the studied ditch bank. In fact, a difference as small as 1.3 kg would fall well within the error of the total erosion and deposition estimates.

Marttila and Kløve (2010b) presented a conceptual model of the processes in the drainage channel, where sediment in the channel is a result of water flow, sheet wash, collapsing ditch banks and undercutting. Both aggradation and degradation can take place in the ditches. Sediment from upstream areas can be stored in the main ditch and later released to be transported with greater flow events. Small-scale ditch bank collapses were also observed and measured in this experiment, and the overall outcome was that the eroded material was deposited in the ditch bottom to be potentially transported later along with greater discharges. Bank erosion can thus be a significant contributor to the sediment load to receiving water courses. A practical problem from the viewpoint of operational forestry associated with ditch bank erosion is the decrease in the ditch depth at locations where the eroded sediments are deposited along with decreasing water flow velocity. Reduced drainage efficiency may soon create a need for new ditch cleaning.

Frost heave was found to be a reversible process in the sense that the elevation change caused by frost was reverted after frost melting at all locations of the ditch bank except the lower section (Fig. 6). A plausible explanation for not detecting an elevation decrease in the lower section is the fact that the reversion of frost heave was masked by the deposition of soil eroded from the upper parts and that the frost heave did not extend to the entire area of the lower section, which was partly residing below the water level of the ditch. It is well known that frost heave can affect the soil surface, especially through the formation of ice needles. These needles contribute to bank erosion rates because their melting results in a loosening of soil on the bank surface (Lawler 1986, Stott 1997). Although the ice needles and dislodged particles on them were observed, the amount of erosion caused by this process was probably too small to be clearly detected by our measurements. However, a heavy rainfall event after the freeze-thaw cycle could have caused more erosion because of the loosened soil surface material. Thus it is possible that the effects of freeze-thaw process could not be fully quantified because of the short measurement period. Silver and Joensuu (2005) stated that the soil frost induced bank collapse was the main reason for the lowering of ditches. In our study, clear bank collapse by frost was not observed. But it should be noted that the freeze-thaw cycle occurred only once, and repeated cycles could have more visible impacts. In addition to the frost heave, the shrinkage and swelling of soil can lead to the deformation of the soil structure through changes in soil moisture content. These phenomena are typical in clay soil (Warsta *et al.* 2013) as well as in peat soil (Oleszczuk and Brandyk 2008). In our experiment, the soil was sandy loam, which is not susceptible to shrinkage and swelling.

Applicability of the pin meter for detecting ditch bank erosion

Pin meter was used in various studies to measure soil surface profile in detail (Table 1). A pin meter similar to this study was applied in the USA by Kornecki *et al.* (2008) to measure sediment loss and deposition in quarter drains. The main difference between their pin meter and the one used in this study was the dimension of the pin meter. Their device was smaller in terms of the measurement range and number of pins. Kornecki *et al.* (2008) were satisfied with the performance of their measuring device and reported that it was well-suited for the erosion measurements in small surface ditches having a width equal to the length of the pin meter and a depth down to 0.25 m. Ferrick and Gatto (2005) applied a sliding pin meter on the laboratory scale to measure rill cross-sections and water surface using varying artificial runoff events and different soil freezing and thawing conditions. García Moreno *et al.* (2008) used a pin meter to estimate surface roughness of a bare field in central Spain. Pin meters were reported to be reliable, easy, and low-cost devices to obtain elevation data. Our pin meter (Fig. 3) provided data from a clearly longer distance than the previous devices and allowed the performance of erosion measurements in a 2 m wide and 1 m deep drainage ditch when used in an inclined position. The use of our device was not as effortless as the small pin meters, and efficient operation (carrying the pin meter and photographing) required at least three persons. The pin meters used by Kornecki *et al.* (2008), Ferrick and Gatto (2005), García Moreno *et al.* (2008) and Vidal Vázquez *et al.* (2010) were used on bare soil or water surface. In our experiment, the pin meter was also used to measure the ditch bottom soil surface below the open water level. The measurements from under the water have difficulties: the results are more uncertain because the saturated soil in the bottom of the ditch can be loose and it is thus difficult to assess the actual level of the ditch bottom.

Based on the validation photographs, the accuracy of the readings of our pin meter was ±5 mm, whereas Kornecki *et al.* (2008) using a direct visual detection of the pin meter readings reported an accuracy of ±1 mm. Even though some of the accuracy is lost by estimating the readings from the photographs rather than measuring them straight from the pin meter, the system allows much faster measurements, which is essential when the numbers of pins and cross-sections are large. Laser scanning would be able to produce a more accurate model of the soil surface [accuracy of 0.5 mm reported by Darboux and Huang (2003)] than pin meters, but was not used here because laser scanning would not allow for underwater measurements, particularly in peatland areas with turbid waters.

Table 1. Application of pin meter method in different studies.

Study	Measurement range (m)	Number of pins used	Pin spacing (m)	Used for	Where applied
Ferrick and Gatto (2005)	0.37	–	–	rill cross-sections	laboratory
García Moreno *et al.* (2008)	1.00	50	0.02	soil surface roughness	agricultural field, Spain
Kornecki *et al.* (2008)	0.68	19	0.038	erosion and deposition	quarter ditch, agricultural field, USA
Vidal Vázquez *et al.* (2010)	1.35	55	0.025	soil surface roughness	agricultural field, Brazil
This study	1.42 (max 2.28)	72 (max 115)	0.02	erosion and deposition	forest ditch bank, Finland

The pin meter used in our study is an example of contact devices for measuring microtopography (e.g. Jester and Klik 2005). Compared with non-contact devices, such as laser scanning and stereophotographs, the resolution and accuracy of the pin meter is limited. Still the pin meter was able to reveal the elevation changes that were shown to be much larger than the measurement accuracy of the device.

Typical methods to generate digital elevation models, i.e. to interpolate the values between measurement points, include geostatistical techniques (e.g. kriging) and neighbourhood approaches (e.g. inverse distance weighting). No method has proven to be clearly better than others in the derivation of digital elevation models (Chaplot *et al*. 2006). The challenge related to application of kriging in this study was the fact that the pin locations could be pointed out from the interpolated surface. An example of this bias can be seen in Fig. 6d, especially in the upper parts of the measurement area, where the pin measurement lines stand out as erosion or deposition while adjacent areas indicate no changes in the profile. These biases are affected by the differences in the measurement resolution in the different directions and the parameters of the kriging estimation. However, the results of the sensitivity analysis suggested that the biases related to the kriging estimates were small and did not mask the measured erosion and deposition processes occurring in the ditch bank.

Conclusions

The results of this study suggest that bank erosion was an important mechanism for generating suspended sediment load from peatland drainage areas. The bank erosion occurs soon after ditch cleaning, the eroded soil is deposited in the bottom area of the ditch bank, where the sediments are susceptible for transport further along the ditch network. Erosion mostly occurred when the average level of the water table was the highest between the measurement times. The total erosion was 41 kg m^{-1} within the studied stretch and the lowest third of the bank area gained an estimated soil mass of 29 kg m^{-1} (21 $dm^3\,m^{-1}$) from the upper parts of the bank. Frost heave affected the ditch bank surface during a cold spell and increased the bank elevation, which was mostly returned to pre-frost levels after the air temperature rose above 0 °C. The quantification of these mechanisms contributes to the understanding of source area processes which is important background for designing water protection methods in drained peatland forests.

The measurement method (pin meter) was found to be a workable device for detecting the erosion-induced changes (1–15 cm) in the ditch dimensions and identifying the main source area processes in the field conditions, although it is laborious and can only be used to measure relatively small areas. Further studies concerning sediment load from ditch cleaning in peatland forest areas should focus on the process of transportation of the eroded soil in the ditch network. Other erosion mechanisms than seepage-induced erosion should also be investigated. The factors and mechanisms controlling bank stabilization also need future research.

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