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Evaluation of erosion and surface roughness in peatland forest ditches using pin meter measurements and terrestrial laser scanning

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ABSTRACT: Anthropogenic activities on peatlands, such as drainage, can increase sediment transport and deposition downstream resulting in harmful ecological impacts. The objective of this study was to quantify changes in erosion/deposition quantities and surface roughness in peatland forest ditches by measuring changes in ditch cross-sections and surface microtopography with two alternative methods: manual pin meter and terrestrial laser scanning (TSL). The methods were applied to a peat ditch and a ditch with a thin peat layer overlaying erosion sensitive mineral soil within a period of two years following ditch cleaning. The results showed that erosion was greater in the ditch with exposed mineral soil than in the peat ditch. The two methods revealed rather similar estimates of erosion and deposition for the ditch with the thin peat layer where cross-sectional changes were large, whereas the results for smaller scale erosion and deposition at the peat ditch differed. The TLS-based erosion and deposition quantities depended on the size of the sampling window used in the estimations. Surface roughness was smaller when calculated from the pin meter data than from the TLS data. Both methods indicated that roughness increased in the banks of the ditch with a thin peat layer. TLS data showed increased roughness also in the peat ditch. The increase in surface roughness was attributed to erosion and growth of vegetation. Both methods were suitable for the measurements of surface roughness and microtopography at the ditch cross-section scale, but the applicability, rigour, and ease of acquisition of TLS data were more evident. The main disadvantage of the TLS instrument (Leica ScanStation 2) compared with pin meter was that even a shallow layer of humic (dark brown) water prevented detection of the ditch bed. The geomorphological potential of the methods was shown to be limited to detection of surface elevation changes >~0.1 m. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: erosion; ditch cleaning; spatial analysis; topography; terrestrial laser scanning

Introduction

Boreal peatlands cover 80% of the world's peatland area (Wieder *et al.*, 2006). In regions with abundant peatland cover, such as Finland, Sweden, and Russia, peatlands are widely used for forestry (Paavilainen and Päivänen, 1995). In Finland, more than 50% of the 9 Mha of peatlands have been drained with open ditches (Finnish Forest Research Institute, 2014), with the peak years of drainage occurring in the 1960s and 1970s. At present, pristine peatlands are not drained for forestry, but the focus has shifted to the maintenance of existing ditch networks. The maintenance includes the cleaning of old ditches and, to some extent, excavation of new complementary ditches in the drainage area.

Despite its importance in forest growth, cleaning of the ditch network has adverse effects on surface waters due to increased sediment loads that lead to reduced water quality (Joensuu *et al.*, 2002; Marttila and Kløve, 2010a, 2010b; Nieminen *et al.*, 2010), and to the disturbance of aquatic habitats and biota (Bilotta and Brazier, 2008). Thus, water protection methods have been developed and they are operationally applied to reduce the harmful impacts of ditch cleaning (Marttila *et al.*, 2010). However, their implementation requires a better understanding of erosion processes in the source areas. Stenberg *et al.* (2015a, 2015b) raised the importance of assessing and quantifying the processes at the headwater source areas as the eroded soil available for transport within the ditch network is large compared with the observed sediment load at the drainage network outlet. In peatlands, ditch erosion processes differ according to, for instance, variations in peat and underlying mineral soil type. Examples of easily erodible underlying soils in areas of thin peat layer are: silt, sand, and other Quaternary deposits. To advance the studies of erosion processes a reliable method for detecting small changes in ditch topography needs to be developed.

Erosion can be measured from changes in topographical reliefs with erosion pins (Lawler, 1993), pin meter (Kornecki *et al.*, 2008), photogrammetry (Rieke-Zapp and Nearing, 2005), and terrestrial (Day *et al.*, 2013) or airborne (Thoma *et al.*, 2005) laser scanning. Laser scanning produces large sets of point cloud data without disturbing the observed area, as it is based on the travel times of laser pulses from the scanner to the surface elements. The accuracy and spatial density of the points depend on the distance of the scanned target. Thus, terrestrial laser scanning (TLS) is preferred for high-resolution and more accurate data acquisition whereas airborne laser scanning (ALS) is suitable for scanning larger areas, e.g. in forestry (Næsset *et al.*, 2004). TLS has been widely used to assess the topography and erosion of various land surfaces (Resop and Hession, 2010; Day *et al.*, 2013; Vinci *et al.*, 2015) and for determining geometric data of hydraulic models (Milan, 2009) and parameters of vegetated channels, such as blockage factor (Jalonen *et al.*, 2014). Although there are uncertainties caused by factors such as sunlight, rainfall or fog (Reshetyuk, 2006) and wet surfaces (Day *et al.*, 2013) when applying TLS, it is regarded as being superior to the other methods since it quickly and accurately covers large areas without disturbing the surface.

There are only a few studies where TLS has been used to assess the topography of peatlands. Grayson *et al.* (2012) produced TLS-based estimates of blanket bog erosion in an area of 7.6 ha during one winter season in the North Pennines, UK, and achieved different results with TLS and erosion pin measurements: a net increase of 2.5 mm in peat surface height was measured with TLS, while a net surface lowering of 38 mm was measured with erosion pins. They suggested that both results should be treated with caution. Ballhorn *et al.* (2009) used ALS to determine burn scar depths over large areas (27 900 km^2) of Indonesian peatlands and considered laser scanning capable of providing sufficiently accurate results in the inaccessible peatland terrain. In the current study, TLS was preferred to ALS for the detection of ditch topography because of better resolution and accuracy. However, it is not well known how TLS performs in ditches or channels excavated into peat where dark colour and wet surfaces adsorb light and may affect the accuracy of the measurement. Therefore, it remains to be demonstrated in what way TLS can estimate erosion after the cleaning of forest ditches.

Surface roughness is another important environmental parameter to consider. It affects channel flow hydraulics by changing flow velocity and turbulence. Increased roughness slows down the flow velocity, thus also affecting erosion and sediment transport capacity. Characterization of surface roughness has been successfully conducted in many studies with TLS (Haubrock *et al.*, 2009; Brasington *et al.*, 2012; Rychkov *et al.*, 2012; Mills and Fotopoulos, 2013) and pin meter (Gilley and Kottwitz, 1995; García Moreno *et al.*, 2008a). Random roughness is a measure of the spatial variation in surface heights calculated from soil microtopography and is typically used as an index for surface roughness (Cremers *et al.*, 1996). Before ditch cleaning, surface roughness in ditches is high after decades of degradation processes, such as the collapse of ditch banks and vegetation growth. After cleaning, the surface of the ditch is assumed to be rather smooth. Thereafter, erosion and deposition processes change surface roughness conditions and can notably affect the hydraulic properties of the ditch. However, surface roughness and its changes have not been documented after the cleaning of ditches with varying peat thickness.

The main objective of this study is to quantify changes in topography and surface roughness in newly cleaned peatland forest ditches. Based on these changes, the aim is to subsequently illustrate the ways in which erosion and deposition processes occur in a ditch with a thick peat cover, and in another where erosion sensitive mineral soil (stony till) under the thin peat layer is exposed. To assess the reliability of the results a secondary aim is to compare the results of two different methods used to measure surface topography: the pin meter and TLS. These methods have rarely been compared, especially in peatland dominated catchments. The methods are used to quantify both small-scale spatial distribution and aggregated cross-sectional quantity of erosion, deposition, and surface roughness. The geomorphological potential of the methods is assessed by evaluating the statistically significant changes obtained with the pin meter and the TLS data following the method presented by Lane *et al.* (2003). The elevation changes in the excavated part of the ditch are assumed to represent the occurrence of erosion and deposition. In addition, the effect of vegetation growth on the estimated erosion/deposition quantities in the ditches is discussed. Since the environmental impacts of ditch cleaning are most visible soon after excavation, we determine the changes occurring during the first two years after the operation.

Materials and Methods

The study site

The study was conducted at the Koivupuro catchment (Figure 1) in Sotkamo, Eastern Finland (63°53′ N, 28°40′ E). The area of the catchment is 113 ha with the catchment comprising of drained peatland forest (27 ha), open pristine mires, and upland forests underlined by mineral soils. The forests consist mainly of Scots pine (*Pinus sylvestris* L.) mixed with Norway spruce (*Picea abies* L.) and birch (*Betula pendula* Roth). Understorey vegetation includes dwarf shrubs (*Vaccinium vitis-idaea, V. uliginosum, V. myrtillus, Empetrum nigrum*, *Rhododendron tomentosum, Chamaedaphne calyculata)* (Finér *et al.*, 1988). Sedges (*Eriophorum vaginatum, Carex* sp.) and cloudberry (*Rubus chamemorus*) were also present and were the first species to grow in the ditch banks after ditch cleaning, along with mosses (*Sphagnum angustifolium*, *Pleurozium schreberi)*. Mean annual precipitation (1981–2010) in the area was 591 mm and mean annual air temperature +2.3°C (Pirinen *et al.*, 2012). On average, snow covers the ground from late October to the end of April. The drainage network was cleaned with an excavator in August 2011, after which the ditches were typically 1 m deep and had a width of 2 m. The topographic measurements were made at a ditch with a thick (>1.5 m) peat layer (A, Figures 1, 2), and a ditch (B, Figures 1, 2) where peat layer thickness was 0.6 m and 0.3 m in the right and left ditch bank, respectively.

Terrestrial laser scanning

Leica ScanStation 2 was used to gather point cloud data of ditch topography (Figure 3). The scanner was reported to have a range up to 300 m and an accuracy of 6 mm (position) and 4 mm (distance) at 1–50 m (Leica Geosystems AG, 2007). A 4-m-long section of the ditches (A and B) was scanned using two scanner positions (at opposite sides of the ditch) for each date and each ditch. The two point cloud data obtained were merged afterwards with Leica Cyclone software using six Leica Geosystems HDS planar targets that were nailed to trees (three targets on both sides of the ditch) resulting in one point cloud for each ditch and each date. The scanning was carried out during four intensive field campaigns at both ditches: October

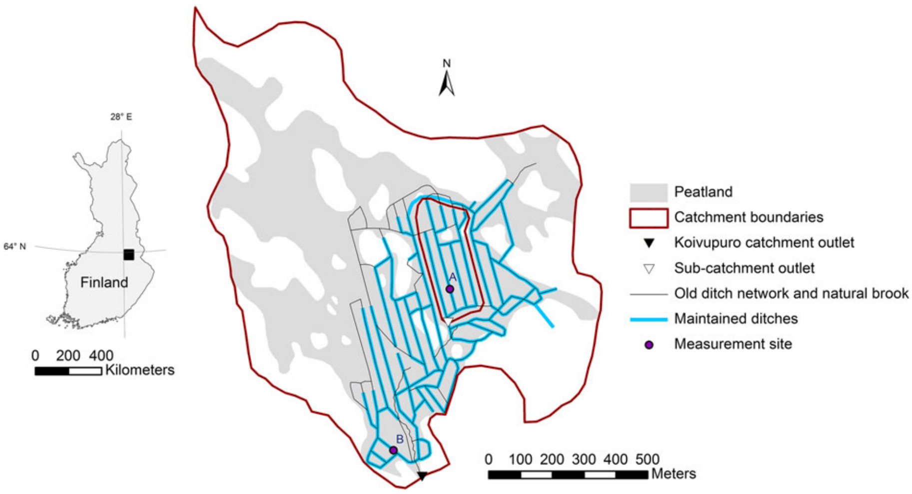

Figure 1. Location of the Koivupuro catchment and the measurement sites in ditches A and B within the drainage network. Ditch A is located at an area with thick (>1.5 m) peat layer in a small sub-catchment and Ditch B in an area with exposed mineral soil close to the main catchment outlet.

2011, May 2012, September 2012, and June 2013. The scanner was repositioned at each date at the same locations of the edges of the ditch banks by placing it in the middle of the pin meter support structures (Figure 2). Erosion was determined as decreased surface elevation, and deposition as increased surface elevation between the different times by using the following procedure (Figure 4). The point clouds from different times were aligned to the same coordinate system by using the CloudCompare software and matching the location of the wooden structures seen in Figure 2. Thereafter, the point clouds were processed with ArcGIS to produce a triangulated irregular network (TIN) by picking the lowest points using four different window sizes: 0.01 m, 0.02 m, 0.10 m, and 0.20 m. Each TIN was converted to a raster (0.02 m × 0.02 m) by using the natural neighbour interpolation and the elevation differences were calculated from these rasters obtained at different times. The elevation differences were multiplied with raster cell size (4×10^{-4} m^2) to obtain volume change for each cell.

To assess the influence of data processing method on the erosion/deposition quantities, ordinary kriging interpolation was also applied. Using the lowest points obtained for 0.1 m and 0.2 m window sizes the data were interpolated to 0.02 m × 0.02 m grid. Erosion/deposition were calculated similarly to the TIN-method.

To obtain the average cross-sections from the TLS data, 0.02 m window size was used to seek the lowest point for each window (cell), thus resulting in a grid with 200×139 calculation cells. Average elevation over the length of the measurement site (4 m) was then calculated for each of the 139 calculation cells as an average of 200 longitudinal cells.

Statistical significance of the elevation differences was assessed using a *t*-test approach proposed by Lane *et al.* (2003). The point data was first detrended by subtracting the average ditch cross-section from the lowest points acquired for the different window sizes. The *t*-statistics were calculated for the elevation difference $z_1 - z_2$ as a function of standard deviations (σ) of the detrended data

$$t = \frac{z_1 - z_2}{\sqrt{\sigma_1^2 + \sigma_2^2}} \tag{1}$$

Figure 2. Ditches A (a–b) and B (c–d) during the first (October 2011) and last (June 2013) measurements. The arrows mark the flow direction.

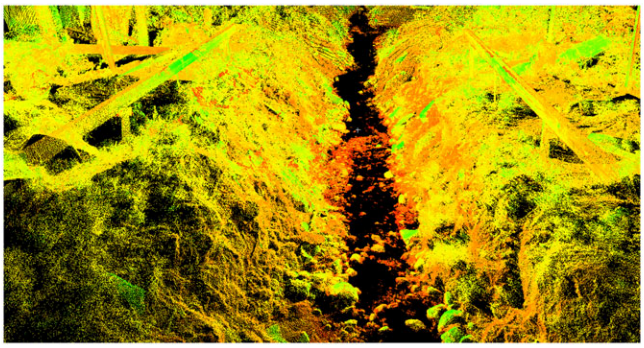

Figure 3. Example of TLS point cloud data (Ditch B, June 2013).

Thresholds for statistically significant elevation changes were obtained with Equation (1) using 68% confidence level ($t = 1$).

Pin meter measurements

The results from TLS data were compared with measurements made with a pin meter on the same ditch sections. The pin meter was supported by wooden structures located at both sides of the ditch (Figure 2) and by a movable support between them that allowed the pin meter to be placed parallel to the ditch bank. The aluminum pins (0.02 m apart from each other) of the pin meter were first carefully lowered to the soil surface and locked. Then the pin meter was lifted out of the ditch in order to photograph the surface profile. The pin meter measurements were made at 0.20 m intervals along a 4-m-long ditch section bound by the wooden structures. The average ditch cross-section was derived from the pin meter data as the mean of 21 pin meter profiles along the ditch section. To calculate the changes in topography (erosion and deposition), the pin meter data were interpolated with ordinary kriging for a 0.02 m × 0.02 m grid. Both sides of the ditches were interpolated separately with the coordinate system rotated in such a way that the z-axis was approximately perpendicular to the ditch bank. The pin meter device and the data processing are described in more detail in Stenberg *et al.* (2015b). In this study

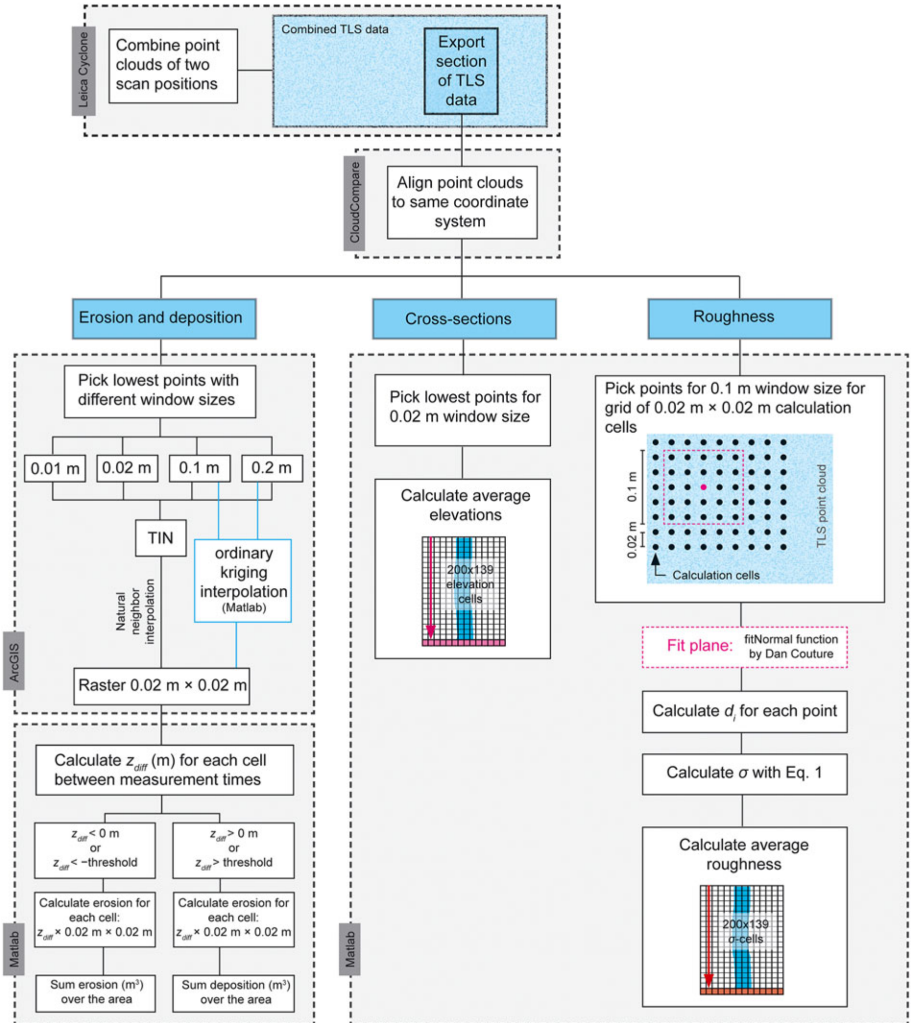

Figure 4. Steps used in calculating erosion, deposition, cross-sections, and roughness of the ditches from TLS data. Notation: z_{diff} is the difference in z-coordinate between the measurement times, d_i is the distance from a point to the fitted plane, and σ is the standard deviation of the d_i.

we reanalyzed the pin meter data of Stenberg *et al.* (2015b) to produce thresholds for statistically significant elevation changes using the *t*-test approach with 68% confidence limit described in the previous section.

Using the TLS data, we also tested what might be a suitable distance between the cross-sections measured by pin meter. The data from Ditch B in June 2013 was chosen for the test because it was known to contain severely eroded parts and more variation in topography than Ditch A. The cross-section points from the TLS data were picked at 0.05, 0.08, 0.20, 0.50, and 1 m distances, and the average cross-sections were calculated and compared.

Random roughness

Random roughness was calculated according to Heritage and Milan (2009) who replaced the traditional detrending of data by using an alternative approach of identifying local roughness. Based on the TLS data, random roughness was calculated for the surfaces of the ditch sections with a 0.02 m resolution using a 0.1 m moving window. To calculate the local random roughness of a single location, points were picked from the TLS data for the window of 0.1 m × 0.1 m. When at least three points were found, the least squares regression was used to identify the plane that best fits the picked points (using fitNormal function for Matlab by Dan Couture) and the distance (d_i) of each point from the plane was calculated. We reanalyzed the pin meter data of Stenberg *et al.* (2015b) to produce another estimate of roughness. A line was fitted to the pin meter points with the least squares method at a resolution of 0.02 m in each cross-section using a line length of 0.1 m. The distance of each point d_i (m) from the line was calculated if at least four points were present in the 0.1 m section. Random roughness (σ, m) is typically expressed as the standard deviation of d_i (Mills and Fotopoulos, 2013; Eitel *et al.*, 2011) and is obtained as

$$\sigma = \sqrt{\frac{1}{N}\sum_1^N (d_i)^2} \qquad (2)$$

where N is the number of d_i. The averages of σ values were then calculated over the length of the ditch to assess average roughness in different parts of the ditch cross-section. We compared the roughness calculated from the TLS and pin meter data in both ditches for the conditions soon after the ditch cleaning (October 2011) and 11 or 20 months afterwards (September 2012 or June 2013). In addition to the cross-sectional change in roughness, the spatial changes in TLS derived roughness were also studied.

Results and Discussion

Spatial variations in erosion and deposition

The high resolution images (Figure 5a, b) depicting Ditch A revealed great variability in small-scale elevation differences with elongated regions of erosion (decreased surface elevation) or deposition (increased surface elevation). Increasing the window size from 0.01 m to 0.10 and 0.20 m (Figure 5c, d) showed larger continuous areas of erosion and deposition. The spatial distribution of the elevation differences calculated in this study from the TLS data corresponded more closely with the reference pin meter data of Stenberg *et al.* (2015b) in Ditch B than in A (Figure 6). At the same time, the elevation differences in Ditch B were in absolute terms larger than in Ditch A. In Ditch B, the major erosion area was clearly observed with both TLS and pin meter data (continuous darker blue regions on the lower half of Figure 6b and 6d). The pin meter data of Stenberg *et al.* (2015b) showed deposition in the bed of Ditch B (Figure 6d) and TLS data of this study agreed with this observation (Figure 6b). In Ditch A, the pin meter data showed deposition mainly on the edges of the ditch bed (Figure 6c), whereas the TLS showed increased elevation in many parts of both ditch banks (Figure 6a). There were also areas of increased elevation in the right bank of Ditch B that were visible with the TLS data (Figure 6b) but not seen in the pin meter data (Figure 6d). In these comparisons, the window size used for the TLS data was 0.10 m, which was considered to be comparable with the resolution of the pin meter data.

The average vertical elevation changes (and their standard deviation) computed from the TLS data were +0.008 m (0.021 m) and +0.001 m (0.012 m) over the right and left sides of Ditch A, respectively (Figure 6a). The corresponding values for the two sides of Ditch B (Figure 6b) were +0.001 m (0.045 m) and −0.027 m (0.056 m). Tuukkanen *et al.* (Unpublished) studied erosion processes in ditch banks using elevation differences measured by erosion pins. Their measurements were conducted in the same ditches as in this study adjacent to the TLS measurement sites. They found that the range of average bank erosion over a period of 20 months (October 2011 to June 2013) was −0.046 m and −0.031 m for the right and left sides of Ditch A, respectively, and −0.006 m and −0.025 m for the right and left sides of Ditch B, respectively. The standard deviation for the erosion pin data varied between 0.007–0.048 m and 0.008–0.036 m in ditches A and B, respectively. The TLS-based erosion and its standard deviation in this study were higher in Ditch B than in A, which contradicts with the erosion-pin measurements by Tuukkanen *et al.* (Unpublished). The difference in the results is probably caused by the high spatial variability in the erosion in the ditch network.

While the impacts of forest ditching and harvesting on erosion and sediment transport from forested catchments is already recognized (Joensuu *et al.*, 2002; Stott, 2005), the spatial variability of erosion in forest ditches has received limited attention. In the UK, Stott (2005) studied the effect of timber harvesting and associated increase in surface runoff on forest ditch bank erosion. The erosion pin measurements by Stott (2005) revealed that in the control sites (not harvested) the average erosion rates were from −0.006 to −0.019 m a^{-1} and the erosion rates in the harvested area were increased to −0.035 m a^{-1} during the two year period of the harvest. The average elevation differences measured in this study with TLS in Ditch B were from −0.007 to −0.012 m a^{-1} (depending on the window size) which corresponds to the rates on the non-harvested area reported by Stott (2005). The current lower rates in Koivupuro are explained by the lower precipitation intensities and the fact that erosion was mainly caused by ditch cleaning without major harvesting activities.

Estimation of net erosion and deposition from surface topography

The erosion volumes calculated from the TLS data showed less variation regardless of the window size than the deposition volumes (Figure 7). The standard deviations of the erosion volumes across the studied window sizes were 2.5 dm^3 m^{-1} and 2.3 dm^3 m^{-1} for ditches A and B, respectively, while the standard deviations of the deposition volumes were 3.2 dm^3 m^{-1} and 7.1 dm^3 m^{-1} for ditches A and B, respectively (Figure 7). These variations were reflected in the net changes of the volume. The impact of window size on the volumetric changes was not systematic; more specifically, increasing window size both increased and

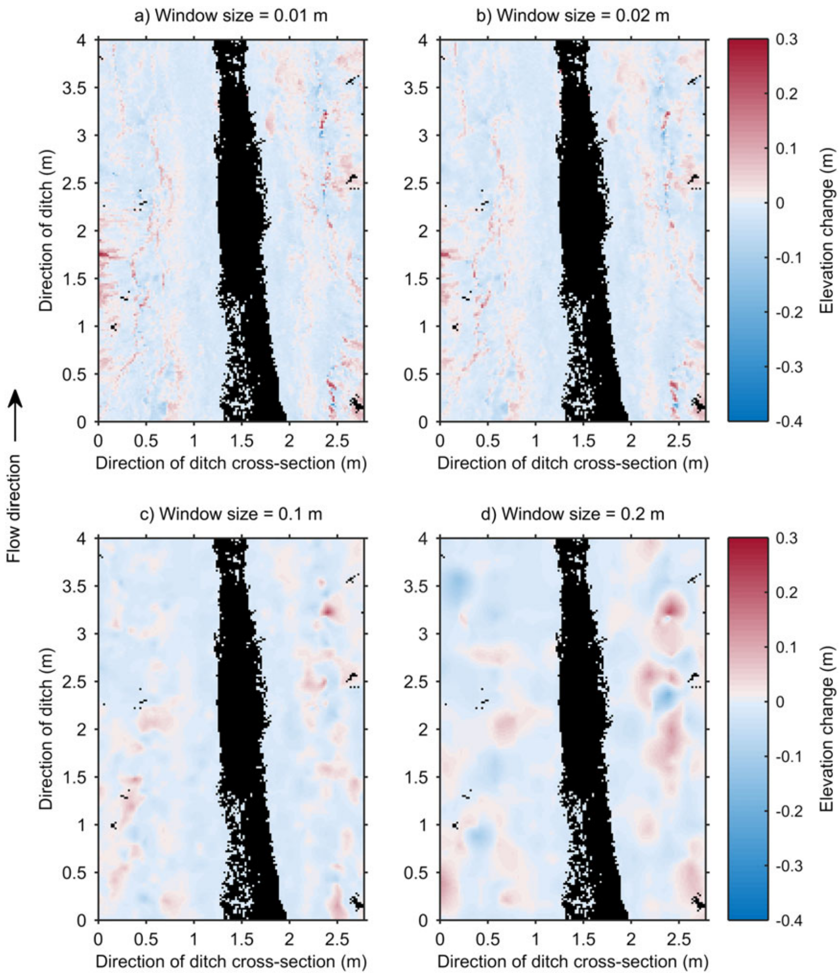

Figure 5. Spatial visualization of erosion (blue) and deposition (red) between October 2011 and June 2013 for a peat ditch (A in Figure 1) calculated with the TIN/NN method using different window sizes: 0.01 m (a), 0.02 m (b), 0.1 m (c), and 0.2 m (d). Black colour represents areas with no TLS data.

decreased the net deposition estimate in ditches A and B, respectively.

The TLS-based deposition and erosion results derived by using different window sizes were also compared with those based on the pin meter data of Stenberg *et al.* (2015b). The erosion and deposition volumes were almost systematically greater in Ditch B than Ditch A with both methods regardless of the applied window size, except for the deposition using the window size of 0.2 m (Figure 7). All deposition quantities based on the TLS data were higher than those derived from the pin meter data in Ditch A (Figure 7a). In Ditch B, the deposition measured by Stenberg *et al.* (2015b) with the pin meter was within the range derived from the TLS data, the window size of 0.02 m giving the closest estimate (Figure 7b). However, erosion estimated with TLS was clearly smaller than that measured with the pin meter in both ditches and more so in Ditch A. Overestimation by the manual method was also noticed by Vinci *et al.* (2015) who measured rill volumes with a pin meter and TLS. Due to the differences in the erosion estimates (Figure 7a), the direction of net change was also different in Ditch A where pin meter measurements showed net erosion and TLS measurements net deposition. However, in Ditch B, the net change was clearly in favor of erosion with both measurement methods (Figure 7b). It should be noted that the no-data areas in the bed of Ditch A (Figure 6a) mask the results. If the bed area was covered by TLS data, the difference between the deposition measured with TLS and pin meter would probably increase while the difference between the erosion quantities would decrease. The same can be said of Ditch B, although the effect would be smaller as the no-data area is also smaller (Figure 6b). As noted by Stenberg *et al.* (2015b), the conversion of volume estimates to mass estimates would pronounce the differences between ditches A and B due to the different bulk densities of peat and mineral soil as well as erosion being most severe in the mineral soil part of the ditch bank (Figure 6b, 6d).

The thresholds for change detection from TLS data calculated with *t*-test using 68% confidence limit were 0.10 m for Ditch A (data from October 2011 and September 2012) and 0.12–0.13 m for Ditch B (data from October 2011 and June 2013). The thresholds were high but varied only a little between the window sizes. The thresholds for the pin meter data were 0.08 m and 0.09–0.11 m for ditches A and B, respectively. Statistically significant erosion and deposition magnitudes were almost negligible in Ditch A (Figure 8a). However, in Ditch B there was clearly significant erosion regardless of the method or window size used (Figure 8b). Figure 8 also shows that the statistically significant erosion differed much less between the interpolation methods (TIN/NN or kriging) than between the measurement methods (TLS or pin meter).

In Ditch B (Figure 7b), the TLS-derived net change during the 611 days was $-0.05...-0.08$ dm^3 m^{-1} d^{-1} whereas the statistically significant net change (Figure 8b) was between -0.03 and -0.04 dm^3 m^{-1} d^{-1}. The result was similar to the short-term study made in Karkkila, Southern Finland, in a ditch with thin peat layer where the net change was -0.05 dm^3 m^{-1} d^{-1} (Stenberg *et al.*, 2015a). In Ditch A, the TLS-derived net change (Figure 7a) was in favor of deposition $+0.01...+0.02$ dm^3 m^{-1} d^{-1} but the statistically significant net change (Figure 8a) was negligible. These results provide source-area evidence that forest ditches extending

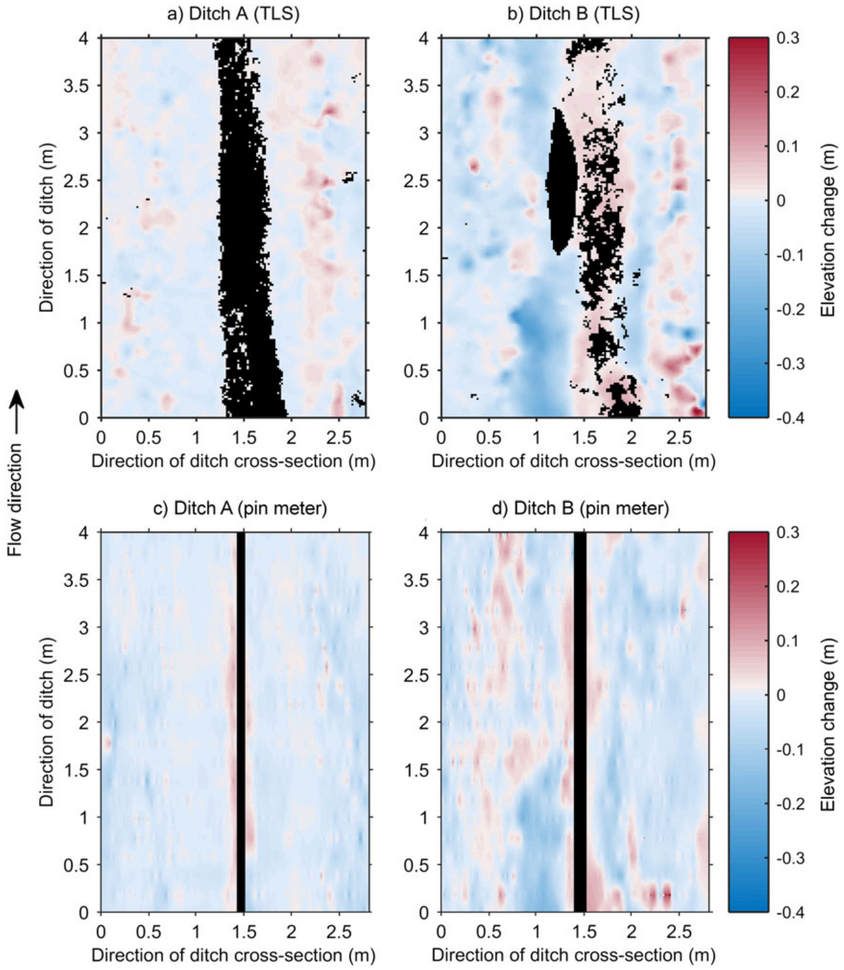

Figure 6. Erosion (blue) and deposition (red) calculated from TLS data (with TIN/NN method) with window size 0.1 m (a–b) and interpolated pin meter data (c–d) between October 2011 and September 2012 for Ditch A with thick peat layer and between October 2011 and June 2013 for Ditch B with thin peat layer. Black colour represents areas with no data.

to mineral soil, such as till in Koivupuro and sandy loam in Karkkila, form the primary erosion risk areas in drained forest catchments. Erosion risk in moderately decomposed peat, such as in Koivupuro, is low because the most decomposed part of the peat erodes first and leaves behind a coarse armor of poorly decomposed peat fibers with a lower risk of erosion (Tuukkanen *et al.*, 2014).

Determination of ditch cross-sections from TLS and pin meter data

Both TLS data of this study and pin meter data of Stenberg *et al.* (2015b) could be processed to derive an average cross-section and its variability within the measured longitudinal section of ditch (Figure 9). Aligning the average cross-sections derived from the TLS and pin meter data in the same coordinate system revealed that the TLS-based cross-section was at a higher level than the pin meter estimate (Figure 9). In Ditch A, the standard deviation of the TLS data was very small in the ditch bed; in addition, the TLS data almost formed a horizontal line (Figure 9a). Thus, in Ditch A, the TLS data were assumed to represent the water level in the ditch while the pin meter data of Stenberg *et al.* (2015b) demonstrated the ditch bed. However, there were only a few TLS data points from the bed area of Ditch A (Figure 6a). The few TLS data points registered from the area of ditch bed were likely to be needles and fallen leaves floating on the water surface or small local deposits in the ditch bed that stuck barely above water level

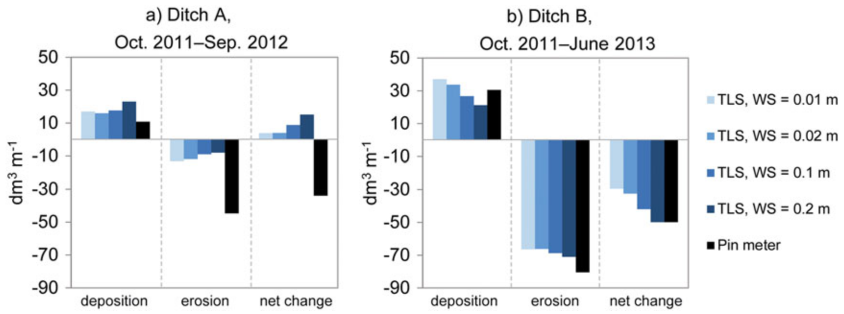

Figure 7. Net increase (deposition) and decrease (erosion) of volumes calculated from terrestrial laser scanning (TLS) data with varying window sizes (WS) with the TIN/NN method and from pin meter data for Ditch A with thick peat layer (a) and Ditch B with thin peat layer (b).

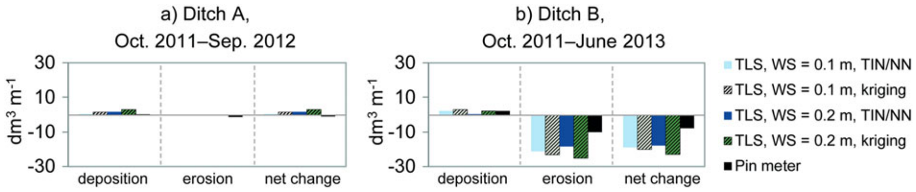

Figure 8. Statistically significant (at 68% confidence level) net increase (deposition) and decrease (erosion) of volumes calculated from terrestrial laser scanning (TLS) data using window sizes (WS) of 0.1 and 0.2 m (with TIN/NN and kriging methods) and from pin meter data for Ditch A with thick peat layer (a) and Ditch B with thin peat layer (b).

(Figure 2a, b). In Ditch B, the standard deviation of the TLS data was greater in the ditch bed (Figure 9b), and there were much less no-data areas at the ditch bed (Figure 6b). In Ditch B, the TLS data points from the ditch bed section probably did not represent the water surface as in Ditch A, but instead the laser penetrated the clear water and was reflected back from the actual ditch bed. The greater standard deviation in the bed of Ditch B is also explained by the slope of the ditch bed being steeper in Ditch B than in Ditch A. TLS did not record data beneath the water surface in Ditch A most likely due to the joint effect of turbid water and the dark peat at the ditch bed. It should also be noted that even though TLS was able to measure under shallow water in Ditch B, the measurements are uncertain because they were not corrected for the refraction of light at the water surface (Milan *et al.*, 2007; Smith *et al.*, 2012). The water flow was turbulent in Ditch B (see Figure 2c–d) which increases the potential for uncertainties (Smith *et al.*, 2012). The pin meter in Stenberg *et al.* (2015b) was able to obtain reliable underwater readings especially when the bed material was firm (e.g. gravel). However, with soft and loose peat bed, such as in Ditch A, it was not easy to determine where the actual ditch bed was as the pins in the pin meter could easily be pushed deeply into the loose peat.

Differences in the average cross-sections derived from the current TLS estimates and from the pin meter estimates of Stenberg *et al.* (2015b) revealed that TLS data showed higher elevation than pin meter data (Figure 9). As the elevation was higher even at the bare parts of the banks, it seemed there were uncertainties in the alignment of the two measurements in the same coordinate system. Due to these uncertainties, it was not advisable to compare the differences in the exact absolute elevations between the measurement methods as such in the same coordinate system. Thus, it is better to compare exact elevations within a method rather than between methods. However, Figure 9 can be used to interpret the key issues concerning the differences in the TLS and pin meter derived cross-sections. The shape of the cross-sections is similar especially at the lower and middle, bare parts of the ditch banks, regardless of the method used in both ditches (Figure 9).

On the upper parts of the banks, the TLS data showed particularly higher elevation than the pin meter data (Figure 9). These differences reveal an important difference between the methods that is related to the measurements of the soil surface at areas with vegetation and woody litter shown in Figure 2. The pin meter of Stenberg *et al.* (2015b) was able to measure ground surface below vegetation that is not too thick or rigid. Problems arose when sticks were thick and prevented the pin from touching the soil surface. TLS, however, measured the vegetation surface even though it was not that thick or dense. The picking of the lowest TLS point in the selected window size (0.02 m) did not guarantee that the point represents ground surface. With greater window size we could increase the possibility of finding a ground point, but in this case the window of 0.02 m was chosen because it was comparable with the pin meter resolution in the direction of the ditch cross-section.

The purpose of the analysis of cross-sections was to demonstrate where erosion and deposition occurred in the ditch since the erosion processes are often conceptualized with cross-sections. Marttila and Kløve (2010b) presented a conceptualization of peatland forest ditch erosion processes which had elements similar to those noted in Ditch B: especially widening of the ditch bed can be seen from the TLS-derived cross-sections in Figure 10b. Aggradation and degradation of ditch bed, stabilization and sorting of bed material, and slumped material (stones) from the upper parts of the bank were also present (Figure 2c–d). The changes in the average cross-sections (Figure 10b) resembled the conceptualization by Stenberg *et al.* (2015a), where bank erosion occurred in the area of seepage face and the eroded soil deposited in the lower bank section and bed of the ditch. However, in the case of Ditch B in Koivupuro, visual observations of bed coarsening (Figure 2c-d) and relatively high flow volumes and velocities in Ditch B suggest that erosion in the lower ditch banks was more related to flowing water than lateral seepage.

Stenberg *et al.* (2015b) estimated the average cross-section of ditches A and B from 21 cross-sections measured with the pin meter with a distance of 0.2 m between the cross-sections.

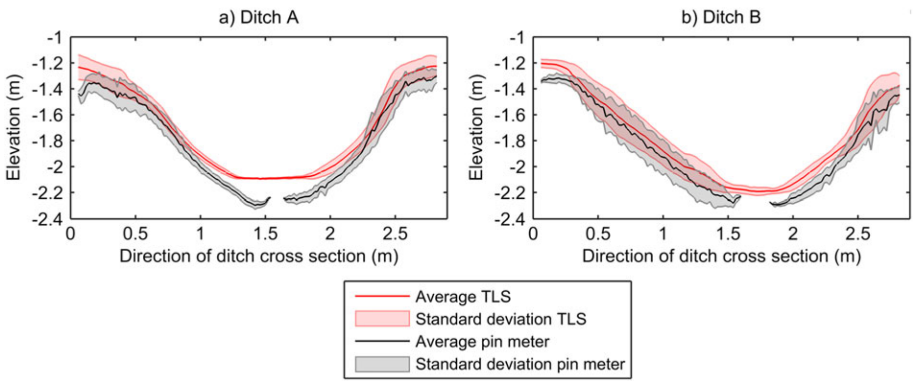

Figure 9. Average cross-section (± standard deviation) calculated from pin meter data and lowest elevation points picked for 0.02 m × 0.02 m grid from TLS data at Ditch A (a) and Ditch B (b) in October 2011.

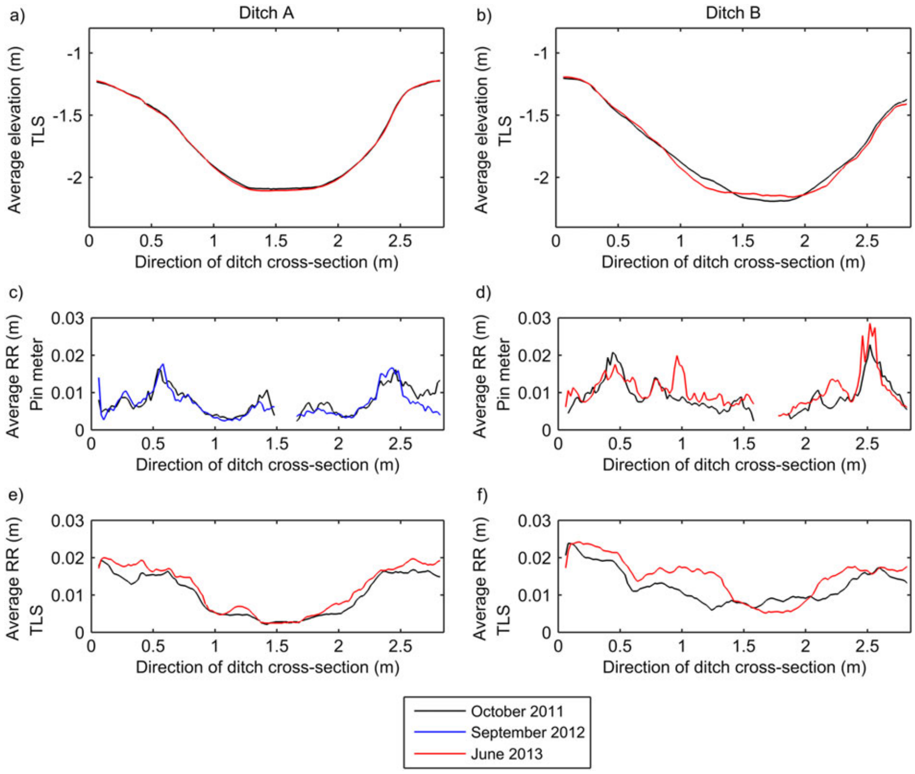

Figure 10. The average cross-sections defined by TLS (a–b) and variation in the average random roughness (RR) calculated for Ditch A with thick peat layer and Ditch B with thin peat layer from pin meter (c–d) and TLS data (e–f).

We used the TLS data of Ditch B to evaluate the effect of cross-section distances on the average cross-section. Picking ditch cross-sections from the TLS data with increasing distance revealed that the average cross-section remained practically the same when the distance changed from 0.05 to 0.08 and 0.2 m. Only at the 0.5 and 1 m distances did small differences in the average cross-sections start to emerge. Thus, the TLS data confirmed that the average cross-section derived from the pin meter measurements by Stenberg *et al.* (2015b) with a distance of 0.2 m produced a good estimate for the average cross-section. However, it should be noted that this result applies only to the average cross-sections of a 4-m-long section of a peatland forest ditch, but not necessarily to a shorter section. Even though the ditch was mechanically cleaned there were irregularities caused by e.g. stones and tree roots affecting the average cross-section over short distances.

Changes in random roughness

Random roughness measured with both TLS and the pin meter was higher in Ditch B (thin peat) than Ditch A (thick peat) (Figure 10c–f, Table I). Roughness calculated from the pin meter data was mainly smaller than the TLS derived roughness, except for the high values in the upper right bank of Ditch B (Figure 10d) which were the result of deep holes that were, in this case, better detected by the pin meter (Figure 9b). Due to the narrow nature of the holes and the angle of the laser beam the full depth of the holes was not recorded by TLS. Roughness measured by TLS was generally higher at ditch banks than in the ditch bed of both ditches (Figure 10e–f). However, such a trend could not be seen in the pin meter derived roughness which was more random. This can be caused by the calculation method and the low resolution of pin meter data compared with the TLS data. The problems with the pin meter measurements on soft bed material, such as saturated peat, could also result in overestimation of roughness in the bed of Ditch A (Figure 10c).

In Ditch B, the temporal changes in roughness were in line with those in the average cross-section: roughness increased where erosion increased and roughness decreased where deposition occurred (Figure 10b and 10f). TLS derived roughness increased in the banks of both ditches, although the increase was greater in Ditch B (Figure 10e–f, Figure 11). Roughness decreased in the bed of Ditch B (Figure 10f and 11b), but no notable changes were observed in Ditch A (Figure 10e and 11a). In addition to the bed of Ditch B, decreased roughness was observed in individual locations on the banks of both ditches (Figure 11). The spatial examination also revealed that the trend was mainly towards increased roughness in both ditches (Figure 11). On average, the roughness indicated by TLS increased 12% at Ditch A and 19% at Ditch B (Table I). The average changes in pin meter derived roughness were −9% and 15% at ditches A and B, respectively (Table I). However, it should be noted that the change in pin meter derived roughness was estimated for a shorter time period in Ditch A than B.

Roughness calculated from the pin meter data showed a similar trend with the TLS-based roughness in Ditch B: roughness increased, although not as clearly as indicated by the TLS data (Figure 10d and 10f). There were not many changes in Ditch A except for the clearly decreased roughness on the upper part of the right ditch bank. There were not enough pin meter measurements to calculate the roughness for the middle of the ditch bed.

TLS has been applied in earlier studies to determine an estimate for surface roughness using different sizes of moving windows. Many of these studies have focused on areas outside the streams (Haubrock *et al.*, 2009; Eitel *et al.*, 2011; Sankey *et al.*, 2012), while other studies report results during low flow conditions for the unsubmerged parts of stream beds or point bars (Heritage and Milan, 2009; Rychkov *et al.*, 2012; Brasington *et al.*, 2012). Roughness is scale-dependent and increases with increasing window size (Haubrock *et al.*, 2009; Sankey *et al.*, 2012); it has been determined with window sizes ranging from a few mm to 1 m (Haubrock *et al.*, 2009; Eitel *et al.*, 2011;

Table I. Average roughness over the measurement area for ditches A and B at different times calculated from TLS and pin meter data with 0.1 m window size

	Average roughness (m), TLS		Average roughness (m), pin meter		
	Oct. 2011	June 2013	Oct. 2011	Sep. 2012	June 2013
Ditch A	0.0105	0.0118	0.0078	0.0071	—
Ditch B	0.0125	0.0149	0.0097	—	0.0112

Heritage and Milan, 2009, Sankey *et al.*, 2012). As the optimal window size depends on the terrain, Heritage and Milan (2009) recommended that the moving window should be the size of the largest visible clast. In the current study, the window size of 0.1 m was considered appropriate for the Koivupuro ditches since it was in the range of earlier studies and could capture most of the small elements and variations but was not overly affected by the slope of the ditch bank. The window size of 0.1 m was about the smallest size that supported the roughness calculations from the pin meter data.

Ditch cleaning in Koivupuro was conducted in August 2011 and the first roughness estimates were given for October 2011. Final estimates were calculated from the June 2013 data resulting in 20 months between the estimates. The changes in roughness during this time were associated with two factors: erosion and vegetation growth. Roughness in the ditch banks can be attributed to small-scale erosion processes caused by rain splash, freeze-thaw effects, desiccation of the bank surface, and geotechnical slope failure. Roughness in the ditch bed, however, can be caused by the aggregated effect of varying flow conditions in the ditches between the measurement times. Haahti *et al.* (2014) used a modelling approach and showed that there is much variation in the flow of the small nested catchment where Ditch A is situated (see Figure 1). During the high flows, especially in the spring snow-melt period, erosion is more likely to occur, whereas during the small flows periods deposition can prevail, making also the roughness processes dynamic. In this study, TLS measurements indicated that roughness increased with increased erosion (Figure 10f). However, there was less erosion in Ditch A (Figures 6, 7), yet roughness was still clearly increased according to TLS measurements (Figure 10e) which refers to the effect of vegetation on the roughness. Increased roughness slows the water flow, thus decreasing the eroding force (Västilä *et al.*, 2016). The increased vegetation cover has been related to decreased bank erosion rates (Stott, 2005).

Cross-sections and surface roughness measures are the basic parameters required in hydraulic models. As the ditch bed widens (Figure 10b), the flow is spread to a wider area and the flow depth is lowered. If the roughness is increased (Figure 10, Table I), the flow velocity becomes slower. However, the TLS based surface roughness estimate is not a parameter that can be used as such in hydraulic models. When the estimates of channel dimensions are combined with streamflow data on water levels, discharge, and slope of the water surface, the roughness parameters of hydraulic models can be determined by calibration against the data (Västilä *et al.*, 2016). Comparing these calibrated values against the TLS based roughness estimates can reveal a relationship between the measured roughness and its parameterization in the hydraulic model. Haahti *et al.* (2014) presented an application of a hydraulic model in the Koivupuro catchment noting that the description of the roughness in modelling of low flows was complicated by the uneven bed of the ditch, which led to a meandering flow with separated flow paths. Combining hydraulic models with TLS data may provide a way forward to refine the description of flow resistance in hydraulic models as shown for vegetated compound channels by Jalonen *et al.* (2014).

Assessment of the applicability of the methods

In this study, we focused on small-scale erosion and deposition processes as well as roughness estimations in 4-m-long sections of ditches. The different aspects of the capabilities of TLS and pin meter methods are assessed in Table II. The clearest differences between the two methods were the impact of vegetation on the results and the ability to measure the submerged areas. The pin meter directly measures the soil surface under the vegetation, while TLS requires post-processing of the data to acquire the soil surface. Water level did not hinder the pin meter

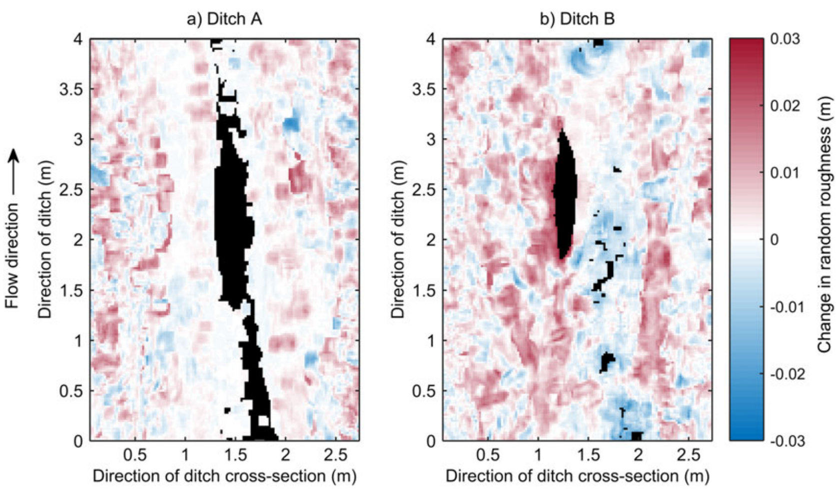

Figure 11. The spatial distribution of changes in random roughness from October 2011 to June 2013 calculated for Ditch A with thick peat layer (a) and Ditch B with thin peat layer (b). Black colour represents the areas with no available data.

Table II. Assessment of the TLS and pin meter methods for different purposes

	TLS	Pin meter
Applicability for		
Small-scale ditch erosion	good	OK
Large-scale ditch erosion	OK	poor
Roughness estimation	good	OK
Ground surface detection	OK	good
Through-water measurements	OK[a]	good
Cross-section detection	good	good
Usage		
Application in the field conditions	OK	OK
Time consuming in the field	OK	poor
Time consuming with data post-processing	OK	poor
The effect of vegetation on the results		
Foliage	poor	good
Sticks and fallen branches	poor	poor

[a]Depends on the type of laser.

measurements and TLS was also partly able to measure under the water. It should, however, be noted that in Koivupuro, the water depth in the ditches A and B was typically around 0.1 m during the time of TLS measurements. The shallow transparent water column allowed the TLS measurements under the water level in Ditch B. If the water level and the turbidity of the water had been higher in Ditch B, the measurements would probably not have been possible. The clearest benefit of the TLS was the ability to quickly cover an area with high resolution while pin meter measurements required great effort. TLS enabled the estimation of spatial variability in the surface roughness as well as the examination of erosion at more detailed spatial resolution. The pin meter results provided an accurate estimate of mean cross-section. In both methods there were challenges with the change detection in the soil profile. The estimation of the thresholds for detecting statistically significant changes revealed that the geomorphological potential of both methods suits the detection of >0.1 m topographical changes in peatland forest conditions.

There are also other methods that could be considered for estimating small-scale erosion and roughness, such as close-range photogrammetry (Aguilar *et al.*, 2009) and shadow analysis for surface roughness (García Moreno *et al.*, 2008b, 2010). A laser-based cost-effective alternative to TLS has been proposed by Lam *et al.* (2015) and structure-from-motion photogrammetry has opened new prospects to capture high-resolution topographic data (Westoby *et al.*, 2012; Micheletti *et al.*, 2015; Smith and Vericat, 2015). However, all of these methods have limited spatial coverage. The scanning of the entire ditch network is not feasible with TLS either, but it could be done with airborne laser scanning (ALS) which reaches an elevation accuracy of 0.05–0.1 m and planimetric accuracy of 0.2–0.8 m (Hyyppä, 2011). Even though allowing better spatial coverage, the accuracy of ALS, in its current state, is not sufficient to detect the average changes in a peatland forest ditch network. However, mini-UAV (unmanned aerial vehicle) based laser scanning has been reported to possess an accuracy of 0.03 m in generating a digital terrain model (Jaakkola *et al.*, 2010). Since mini-UAV measurements would be an advantage in drained peatland forest conditions, they would probably be a feasible option to cover the entire ditch network with tolerable accuracy. However, as demonstrated by the results of this study, the topographical changes in peatland ditches can be very small and thus they might not be captured with mini-UAV measurements.

Conclusions

Pin meter measurements and TLS were applied to estimate erosion, deposition, and changes in surface roughness in peatland forest ditches with different peat layer thickness. Both methods clearly indicated that erosion and increase in surface roughness were greater in the ditch with exposed mineral soil than in the peat ditch. This emphasizes the importance of considering the thickness of the peat layer, when ditch cleaning is carried out with an aim to minimize sediment loads to water courses. The differences in the estimates of net erosion/deposition were clear between the different ditches regardless of the window size used in the TLS-estimates. In the ditch with thin peat layer, the erosion quantities calculated by both methods were larger and more consistent than in the peat ditch. Surface roughness increased more on the ditch banks which was attributed to both erosion and growth of vegetation.

The resolution of change detection was clearly higher with TLS than using the pin meter, as expected, but the major changes were well detected with both methods. However, the thresholds for statistically significant change detection (Lane *et al.*, 2003) from the TLS data (0.10–0.13 m at 68% confidence level) and from the pin meter data (0.08–0.11 m at 68% confidence level) were high which makes reliable estimation of small changes difficult and limits the geomorphological potential of the methods to collapses of ditch banks and other major erosion/deposition spots.

Reliable estimation of roughness requires high resolution elevation data which is readily available with TLS but laborious to acquire with a pin meter. Processing of the pin meter measurements to coordinates was time-consuming and prone to errors. Even though TLS also requires much data processing, it was clearly more efficient in producing data as the resolution and spatial coverage of the data were high. However, cross-sections can be defined with less accurate methods with lower spatial coverage. Thus, the benefits of TLS emerge with roughness estimations where better spatial coverage and a more accurate method is needed. The greatest advantage of the pin meter method was that it provided a reliable estimate of soil surface elevation in vegetated and submerged areas. The results suggested that TLS is well-suited for erosion and roughness assessment in peatland forest ditches while the pin meter is capable of determining cross-sections for hydraulic modelling and erosion with lower resolution.

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