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Modelling depth of drainage ditches in forested peatlands of Finland

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Abstract

Drainage ditches have been dug in peatlands and paludified forests to enhance forest growth in an area of 4.7 Mha in Finland. Because of peat subsidence, bank erosion, sedimentation, and the ingrowth of vegetation ditches deteriorate with time. In this study the shallowing of ditch depth over time was investigated based on a country-wide peatland inventory data measured repeatedly up to four times. Mixed linear models were developed separately for original ditches and maintained ones (cleaned once or twice). After 20 years, the ditches were 20–30 cm shallower than right after the digging. The time since digging was the most important variable explaining the shallowing for both original and maintained ditches. Other variables explaining the ditch shallowing were the digging method (excavator, plough), ditch bed slope, location, and peat layer thickness. The average development of the maintained and original excavator ditches was very similar. The results can be used in assessing decision making concerning ditch cleaning.

Keywords: forest drainage, ditch depth, ditch network maintenance, modelling, peatland

Introduction

In Finland, the intensive drainage of peatlands and paludified forests aiming to enhance the growth of tree stands started in the 1930s and ended in the mid-1990s when the digging of ditches on pristine peatlands virtually ceased. By digging ditches, the soil water table level was lowered which enabled a higher decomposition and nutrient supply, and consequently improved tree growth. Altogether, 4.7 million hectares of peatlands have been drained for forestry (Korhonen et al. 2017) – first by hand, then mainly by plough, and recently by excavator.

Ditches deteriorate with time due to natural processes such as subsidence of the peat layer, ditch bank erosion, and vegetation ingrowth, but also due to damages caused by the harvesting of trees in peatland forests (Paavilainen and Päivänen 1995). If ditches become blocked, the water flow slows down inducing raise in water table levels, which, in turn, may retard growth of the trees (Pelkonen 1975, Heikurainen 1980).

Ditch network maintenance (DNM) is an operation aiming to maintain the water transportation capacity of the drainage ditch network either by the cleaning of old ditches or digging new complementary ditches. Lauhanen et al. (1998), Lauhanen and Ahti (2001), Hökkä and Kojola (2003), and Ahti et al. (2008) have shown that after maintenance of the ditches, a growth response of trees is to be expected. This response varies depending on the soil water conditions before the DNM operation (Sarkkola et al. 2013), geographical location of the tree stand (Ahti et al. 2008), stand stocking, and site quality (Hökkä and Kojola 2003). Because DNM causes sediment and nutrient loads to water courses from the exposed ditch banks and bottoms (Nieminen et al. 2017), careful justification of the need for DNM operation is recommended in practice (Vanhatalo et al. 2015). The necessity of deep good quality ditches for good tree growth has been questioned in recent studies (Sarkkola et al. 2012, 2013), and the biological drainage mediated by the water use of the tree stand has been emphasised (Sarkkola et al. 2010, 2013).

In Finland, several studies investigating the development of drainage ditch depth over time show that the depth becomes shallower very soon after digging (Multamäki 1934, Lukkala 1949, Heikurainen 1957, Timonen 1983, Laine 1986, Lauhanen et al. 1998). Heikurainen (1957) observed that 20-year-old ditches were on average 57 cm deep, i.e. 24–36 cm shallower than newly dug ditches, while Timonen (1983) found that 15-year-old ditches were on average about 70 cm deep, i.e. 21–22% (ca. 20 cm) shallower than after ditching. According to Laine (1986), the average depth of 25-year-old ditches in composite pine mire sites in the middle parts of Finland was 61 cm. It has been generally concluded that a great change in ditch depth occurs during the first decade after digging as a significant volume of water is removed from the peat surface layers (Heikurainen 1957, Timonen 1983) due to which the structure of the loose surface peat collapses and also makes the ditches shallower.

Much less information is available on maintained ditches. Results of the survey study by Silver and Joensuu (2005) in South-West Finland including five- and ten-year-old DNM areas revealed that maintained ditches became shallower faster than original ditches, i.e. about 30 cm in ten years. Erosion just after ditching and vegetation invasion were found to be the most important reasons for changes in ditch depth. Stenberg et al. (2015a, b), Tuukkanen et al. (2016), and Haahti et al. (2016) have investigated ditch bank erosion processes and changes in ditch dimensions but these measurements covered only a period of one to two years after DNM thus being unable to show long-term temporal trends.

Despite the old survey studies on the ditch dimensions after drainage, there is very little information available on the rate of ditch deterioration in the long term. It is known that shallowing occurs largely due to sediment accumulation and peat subsidence. Peat surface subsides rather quickly when the water content of the peat decreases following drainage, which leads to a collapse of the structure of the porous substrate (Sikström and Hökkä 2016, Hillman 1997). Later on, the weight of the increasing tree stand and peat decomposition may cause further subsidence (Sikström and Hökkä 2016, Byrne and Farrell 1997).

A lack of good understanding on ditch deterioration is an important reason why practical guidelines still do not exist for deciding where DNM is and is not needed (Sikström and Hökkä 2016). For example, from the forest management point of view, information on ditch depth development would help to predict the future depth of ditches and to plan consequent DNM in different situations. Although ditch depth reflects soil water conditions only indirectly (cf. Lauhanen et al. 1998), the information can be useful in making management decisions (Hökkä et al. 2000, Koivusalo et al. 2006) because direct quantitative information on soil water conditions is not easily measurable. As DNM is the main source of forestry-induced sediment load to water courses (Finér et al. 2010, Nieminen et al. 2017), its application should be carefully evaluated which, in turn, necessitates a better understanding on the actual need for DNM. The change rate in the ditch depth is necessary information when predicting the fate of drained peatlands from the viewpoints of wood production, carbon balance or restoration.

The aim of this study was to quantify the general pattern of forest ditch shallowing and to develop models that would be able to predict ditch depth as a function of time since digging and different site variables. The data used in this study were a systematic sub-sample of the 7th National Forest Inventory (NFI7) field plots representing the whole geographical range, where forest drainage has been applied in Finland.

Materials and methods

Data

The so called SINKA database was used in this study. SINKA is a network of permanent forest growth plots set up in drained peatland stands as described in Penttilä and Honkanen (1986). The SINKA plots were sampled by stratified systematic sampling from NFI7 sample plots that were located on drained peatlands. Sampling units included stands that were in satisfactory silvicultural condition and homogeneous with respect to the site and stand developmental stage. A SINKA plot was composed of a cluster of three circular sample plots located 40 m apart within the sample stand. The size of the plot was determined by stand density: the target number of trees was 30 and that of sample trees was 10 in each sample plot. In each sample plot, numerous characteristics describing the stand, the trees, site properties, and drainage situation were recorded (Penttilä and Honkanen 1986).

The field measurements were carried out in 1984–2009 in northern Finland and in 2001–2013 in southern Finland. Thus, the whole SINKA data included one to four measurements of the same stands carried out mostly at five (but in some cases 15) year (growing season) intervals with the number of measurements varying from stand to stand (e.g. because of loss of stands due to cuttings, and extending the sample frame to southern Finland in 2001; see Repola et al. 2018). The oldest forest drainage operations found in the data were carried out in the 1910s but in most of the stands the first-time drainage was made in the 1960s or 1970s. For example, a more detailed description of the data is found in Penttilä and Honkanen (1986) or Repola et al. (2018).

Field measurements

In this study, variables describing the site and ditch properties and drainage status were investigated. The original peatland site type was determined in the field according to Heikurainen (1978) and later Laine and Vasander (2005). North and east coordinates and elevation were determined from the map or by using a GPS device. The peat layer thickness was measured down to a depth of 2 m at each subplot with an accuracy of 1 cm.

All ditches within 30-m distance (50-m distance for parallel oriented ditches) from the sample plot centre were recorded and numbered consequently and their orientation was determined. The bed slope (%) of each ditch was determined from the ditch line with a clinometer. Ditch depth refers to the difference in elevation between the soil surface and the ditch bottom at a point, where a line drawn from the plot centre hits the central line of the ditch at a right angle (Penttilä and Honkanen 1986). The vertical distance between the ditch bottom and a stick installed at a level of the soil surface across the ditch was measured at an accuracy of 1 cm and recorded as the ditch depth. Having soil surface as the reference level involves uncertainty and possible sources of measurement error because of, for example, a somewhat vague determination of the average soil surface level due to hummocks and hollows as well as the varying thickness of the humus layer, along with the sporadic manner of the erosion of ditch walls and the bottom at the measurement point between measurement occasions. The exact determination of the measurement point was an attempt to control the depth measurement and simultaneously to minimise the time and cost of these measurements. The error related to the determination of the soil surface level could have been diminished only by adding more measurement points. Because only one point was available, this means that also the results of ditch depth and the model predictions should be regarded as a mean of a large sample.

The ditch width at the soil surface was measured at the same point as the depth. The digging method (e.g. hand, explosive, plough, excavator) and the ditch condition were also assessed in the field, if possible. The digging year was obtained from drainage documents and the time since digging was calculated as the number of years between the measurement date and the year when the ditch was last dug, i.e., after ditch cleaning, the counting of the number of years started over again.

The basic data composed of measurements of the ditch depth subjected to the same ditches and measured at the same points for 1–4 times. All sample plots, in which at least one ditch was measured once were included in the data set. In each measurement occasion, the ditches were classified as an original ditch or a maintained ditch. In cases where the ditch cleaning operation had occurred, the ditch was classified as a maintained ditch. A possible complementary ditch dug in-between two successive measurements was added as a new ditch.

Data management

Since the year of ditching was a crucial variable in the analysis, several stands were omitted from the data because it was not possible to determine the exact year of digging. In addition, ditches that had been dug by hand or created by explosives were omitted.

Concerning the ditch depth, the following requirements were set for accepted recordings: the ditch depth had to be within 0.2 and 1.2 m, because ditches shallower than 0.2 m were considered to be so badly deteriorated that they no longer had any impact on drainage. Ditches deeper than 1.2 m were either significantly eroded or dug to serve as a main ditch.

In the absence of disturbances, successive measurements of the same ditch should generally result in a slightly shallower depth following a period of five years. However, a relatively large variation around the mean shallowing pattern was observed in the data. An increase in the ditch depth was obvious if the DNM operation had been carried out in-between the measurement rounds. Despite that consideration, it appeared that a significant deepening of several ditches had occurred although no DNM operations were recorded suggesting that not all DNM operations had been noticed in the field. Additionally, in some ditches the shallowing rate was clearly greater than the mean in the data.

To establish a rule for detecting outliers from an acceptable variation of the measurements of ditch depth, an average shallowing rate and its standard deviation was calculated for the three periods between the four successive measurement occasions (Table 1). As expected, the average annual shallowing rate of ditches decreased from that between the first two measurements to that between the last two measurements. For each period, any change in ditch depth that was greater than the mean $\pm$ the threefold standard deviation was considered as a possible outlier. Those outliers that were related to ditch deepening were checked further. If the ditch had deepened more than 10 cm and down to a depth of at least 90 cm, or at least to 80 cm with increased ditch width, it was reclassified as a maintained ditch in the follow-up measurements. Such a reclassification from the original to the maintained ditch was done for 49 ditches altogether, for which no DNM operations were recorded in the original data. Additionally, there were 17 measurements that were regarded as outliers and were removed from the data set due to a large deepening which could not be connected to DNM (based on conditions defined above). The number of those outliers that were removed from the data set due to a greater shallowing than the mean $\pm$ the 3-fold standard error was 105.

The number of sample stands and ditch measurements were 423 and 5222 in the original ditch data set, and 247 and 2564 in the maintained ditch data set, respectively. The average depth of the original ditches was 57 cm at an aver-

Table 1. Average shallowing rate of original ditches with at least 3 measurements per ditch and its standard error between different measurement occasions

	Measurements 1–2	Measurements 2–3	Measurements 3–4
Mean shallowing rate, cm year^{-1}	–0.88	–0.60	–0.30
SE of mean	1.88	1.13	1.28
Age of ditches	20.5	27.9	35.2
n	855	855	454

Average ditch ages are also indicated. *n* stands for the number of ditches (*SE* stands for standard error).

age time of 25 years since the previous digging (Table 2). The maintained ditches were deeper (71 cm) on average, but also more recently dug (13 years since the previous digging).

The drained peatland site type classification system defined by Laine (1989) was utilised in the analysis in a way that site type groups I and II were distinguished and tested as explanatory variables. Site type I represents drier, generally shallow-peated, originally forested, productive genuine peatland forest sites (GS), while site type group II represents originally deep-peated, wet, sparsely stocked, non-productive composite peatland sites (CS).

Methods

Separate data sets were composed and the models were developed for the original and maintained ditches because it was assumed that the dynamics in ditch depth were dissimilar although the mean trends of excavator-made original and maintained ditches were close to each other (Figure 1). Ditches made by plough were clearly shallower at the same age.

Ditch depth without transformations was used as the response variable in both models. The methods of mixed linear models (Searle 1987) were used in the analysis because of the hierarchically structured data with ditches nested within stands and measurements nested within ditches. The models fixed part consisted of the age of the ditch, different site variables, and the ditching method (plough, excavator). Necessary transformations were made to linearize the relationship between the response and explanatory variables.

In the random part, variation among the sample stands, among ditches within the sample stand, and among measurement occasions within the ditch were addressed. A constant correlation structure was assumed for the residuals at the measurement level.

The mixed procedure in SAS was used in the parameter estimation (SAS 2016). The final models were selected based on logical model behaviour, non-existent trends in residuals against explanatory variables, and the low AIC (Akaike information criterion) value.

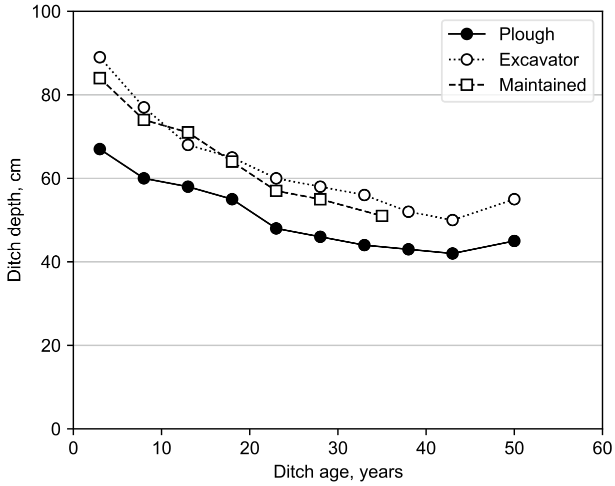

Figure 1. Average depth of original ditches made by plough or excavator, and maintained ditches made by excavator as a function of ditch age

Results

For the depth of old original ditches, the most important explanatory variable was the time since the last digging, termed as ditch age from here on, with a negative power ($Age^{-0.2}$, Table 3). Ditch age in logarithmic scale was also included to improve the model fit. The difference between the two main site type groups was non-significant. The digging method influenced the model intercept in a way that ditches made by plough were clearly shallower than those made by excavator (Table 3, Figure 1), but there was no significant difference in the slope. Peat thickness influenced depth in a non-linear manner, i.e. depth increased with increasing peat thickness, but there was a culmination point at a thickness of 1.5 m. Because of this, a maximum value of 1.2 m corresponding to maximum ditch depth in the data was used for ditch peat thick-

Table 2. Mean, minimum and maximum values of site characteristics of the ditch depth modelling data

Characteristic	Data set					
	Original ditches			Maintained ditches		
	mean	min	max	mean	min	max
N-coordinate, km	721.8	670.7	750.4	714.8	670.6	745.0
E-coordinate, km	346.4	325.3	370.5	347.3	325.3	370.5
Accumulated temperature	970	735	1342	1007	772	1338
Altitude, m	125	2	300	126	0	270
Ditch bed slope, %	0.62	0	4	0.46	0	4
Ditch depth, cm	57	20	120	71	22	120
Peat thickness, m	0.61	0.01	2.00	0.65	0.01	1.20
Ditch age, years	25	1	73	13	1	38
Year of initial ditching	1970	1930	1987	1955	1907	1988
Years since 1. DNM	-	-	-	14	1	42
Years since 2. DNM	-	-	-	7	1	19
Number of stands	423			247		
Number of measurements	5222			2564		

ness (see Heikurainen 1957). Ditches were deeper in locations, where the ditch bed slope was greater (Table 3). There was a significant negative interaction between ditch age and peat thickness, suggesting that ditches of the same age were deeper in thick-peated sites but became shallower faster in thick-peated sites than in shallow-peated sites. The data suggested that the shallowing rate generally slowed down after an age of 35 years. That effect was partly addressed by a variable Age_{35}^2 which slightly reduced the shallowing rate.

The inverse of ditch age ($Age^{-0.2}$) was also the most important explanatory variable explaining the depth of maintained ditches (Table 3). A transformation like that for original ditches was used for peat thickness. Ditch bed slope was significant, but the impact was less pronounced than that for original ditches (Table 3). On average, the maintained ditches were shallower in the south, but according to the interaction term (Ncoord*Age), the rate of shallowing increased towards the north. A negative interaction between ditch age and peat thickness was significant.

In the random part of the model, the within-stand variation in ditch depth was the smallest (ca. 13%) and the between-stand variation (50% and 53%) was the largest component in both models. The residual variability related to the successive measurements (combined with the possible depth measurement error) was 33% and 36% in the original and maintained models, respectively.

The models for original ditches predicted too shallow a depth for ditches >40 years of age (Figure 2). The slower shallowing rate was not possible to be properly addressed by the models due to the low number of observations from the old ditches. For young ditches (<10 years), the bias was likely due to the low number of observations, especially for plough ditches (eight and nine observations for <5 and <10-year age classes). The model for maintained ditches appears to over-predict the ditch depth for all ages (average bias –1.29 cm) and there was an increasing trend along the ditch age (Figure 3). However, when the random effects are omitted from the model, the bias disappears. Thus, the bias reflects unbalanced data, where ditch depth and the number of observations within a stand are positively correlated. In the mixed model estimation, the model appears biased at the observation level (Figure 3).

Discussion

In this study, the models were developed to quantify the post-drainage development of the forest ditch depth

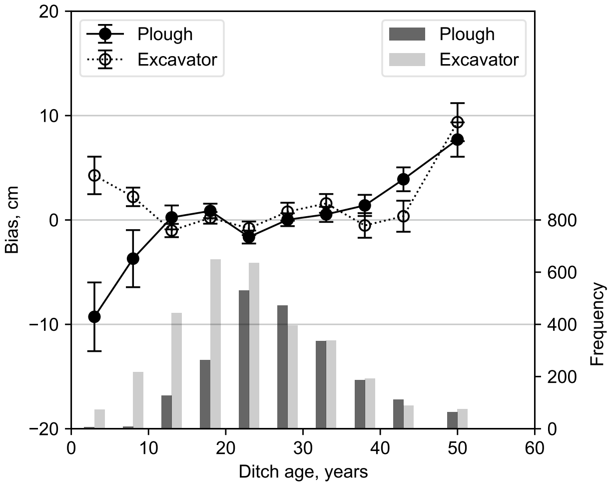

Figure 2. Bias of models for original ditches made by plough or excavator as a function of ditch age

Bars indicate the standard error of the mean. Frequency indicates number of observations in age class.

Table 3. Models for predicting ditch depth in original and maintained (once or twice) ditches in drained peatland forests (*SE* stands for standard error)

Parameter	Model: Original Ditch, Response variable: Ditch depth – Coefficient	*SE*	Model: Maintained ditch, Response variable: Ditch depth – Coefficient	*SE*
Fixed part				
Intercept	49.139	4.456	223.21	44.778
$Age^{-0.2}$	23.981	6.244	18.414	4.502
Age	–0.343	0.057	–5.682	1.701
Age*Peat120	–0.404	0.055	-	
Age_{35}^2	0.00134	0.0004	-	
Plough	–12.085	0.817	-	
Peat120	17.961	1.666	6.749	1.488
Ditch bed slope	3.224	0.254	1.494	0.649
Ncoord			–0.222	0.062
Ncoord*Age			0.00698	0.00236
Random part				
var(Stand)	115.070	10.262	164.720	19.132
var(Ditch)	32.542	3.174	42.053	5.659
var(Measurement)	83.178	1.805	104.800	3.354

Notes:
Age – time since ditch digging to measurement date, years;
Age_{35}^2 – age squared for ditches made more than 35 yr. ago, otherwise 0;
Plough – ditch made by plough (class indication variable 0/1);
Peat120 – peat thickness, m (maximum = 1.20 m);
Ditch bed slope – slope of the ditch bed, %;
Ncoord – north coordinate/100, km;
var(Stand) – variance among stands;
var(Ditch) – variance among ditches within stands;
var(Measurement) – variance among measurement occasions within ditches.

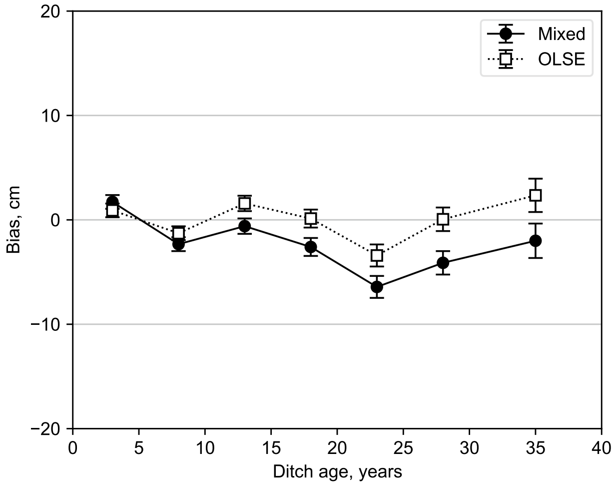

Figure 3. Bias of the mixed model and the ordinary least square (OLSE) model for maintained ditches as a function of ditch age Bars indicate the standard error of the mean.

over time. Such models have not previously been presented. In previous studies, cross-sectional survey data sets representing smaller regions and a situation at one time point were only used (e.g. Multamäki 1934, Heikurainen 1957, Heikurainen 1980, Timonen 1983, Laine 1986, Lauhanen et al. 1998). In this study, a large sample of drained peatland ditches representing a wide range of ditch ages, site types, and geographical regions enabled the building of longitudinal data with better possibilities to understand the temporal dynamics of ditch depth.

Although based on more representative data, the models of this study do not indicate direct causal relationships between ditch depth and factors affecting the change in depth. This is because the data were collected for the purposes of tree growth studies and some variables that may be relevant to understanding the shallowing process, for example, properties of the soil profile, were not observed. Studies such as Tuukkanen et al. (2014, 2016), Haahti et al. (2014, 2016) and Stenberg et al. (2015a, 2015b, 2016) were aimed at finding factors that cause ditch erosion. However, the models developed in this study merely serve as a tool to estimate the average depth of ditches at varying ages and under different environmental conditions, but the development of some specific ditch cannot be predicted accurately. This is because of the large measurement error related to the observed ditch depth in the data. It should also be noticed that the number of observations is limited for ditches of more than 40 years of age in the data.

When comparing the means given in previous studies for ditch depth to those of this study, the mean ditch depths observed by Heikurainen (1957) at 20 years of age (57 cm) and Laine (1986) at 25 years of age (61 cm) are rather close to the average depth of original ditches in the data of this study, i.e. 57 cm at an age of 25 years. In the study performed by Timonen (1983), plough ditches and excavator ditches are 12 cm and 4 cm deeper at the age of 15 years than depths estimated from the data of this study, respectively.

It transpired that the dynamics of the original and maintained (cleaned) excavator ditches were slightly dissimilar, due to which the separate models were constructed. The most important variable explaining the variation of depth between both original ditches and maintained ditches was the age of the ditch, i.e. the time elapsed since the previous digging. This is in line with observations of earlier studies which have concluded that ditch dimension changes as time since digging increases, which is especially strong during the first few decades after the operation (Lukkala 1949, Heikurainen 1957, Timonen 1983). The long-time span covered by this study indicated that the rate of shallowing of original ditches is faster for the first ten years but slows down after 35 years (Figure 1).

The primary reason for the change in depth is obviously the rather quick subsidence of the peat surface when the water content of the peat rapidly decreases following drainage and the structure of the substrate collapses due to a lack of support in the air filled pores (Hillman 1997, Sikström and Hökkä 2016). After that, peat subsidence continues due to, for example, peat compression caused by the increasing weight of the tree stand (Byrne and Farrell 1997, Sikström and Hökkä 2016). Minkkinen and Laine (1998) concluded that peat in Finnish pine mires subsided by 22 cm on average in 60 years, most significantly in deep-peated and N-rich sites. In Scotland, an average of 57 cm peat subsidence was reported for 50 years after drainage and afforestation, although most of the changes occurred during the first 30 years (Sloan et al. 2019). Increases in aeration of the surface peat after drainage accelerate decomposition, thereby increasing the bulk density of the peat (Minkkinen and Laine 1998). Continuing peat decomposition may partly be responsible for the later shallowing of ditches.

The second main reason for ditch depth shallowing is the change of the ditch form after drainage due to different erosion processes. Depending on the soil properties, a ditch may keep its form for a long time or lose it rather quickly. Poorly or moderately decomposed fibric peat (e.g. Silver and Joensuu 2005), gravel, and clay soils maintain their form rather well, while highly decomposed peat (Tuukkanen et al. 2014), and silty (Silver and Joensuu 2005) or sandy subsoils are susceptible to erosion. In small streams like drainage ditches, more erosion is caused by subaerial processes such as desiccation and soil freezing (Lawler 1992, Silver and Joensuu 2005). Erosion from ditch banks supplies material to be deposited into the ditch bed thus making ditches shallower. Ditch bank erosion takes place during the first few years after digging (Silver and Joensuu 2005, Stenberg et al. 2015a, b, Tuukkanen et al. 2016) and contributes to the quicker shallowing rate soon after drainage.

Ditch bed erosion is caused by flowing water (Robert 2014). In general, if the bed slope is negligible, there is no flow and the material is deposited close to its origin thus making a ditch shallower. On a sloping surface, a ditch may keep its depth better than in a flat surface (Heikurainen 1980). A higher ditch bed slope resulted in deeper ditches on average in this study, which is probably a consequence of the transportation of the eroded material with flowing water away from its origin, but also possibly because of ditch bed erosion due to water movement (Haahti et al. 2014). According to Tuukkanen et al. (2016), the deposition occurred mainly on gentle slopes and local depressions, highlighting the importance of ditch macro-topography for transport and deposition processes. In ditches with very small or no slopes, revegetation by peatland species, commonly *Eriophorum vaginatum* or *Sphagnum* moss, may also take place faster and block the water movement which, in turn, enhances the shallowing of the ditch (Silver and Joensuu 2005, Holden et al. 2007).

Concerning the original ditches, a clear difference was found between the digging methods: ditches made by plough were more than 10 cm shallower than those made by excavator at the same age (Figure 1). A similar difference was found by Timonen (1983) for ditches dug in shallow-peated (<0.4 m) sites. With a thicker peat layer, the shallowing rate was similar in both digging methods. It is likely that the ploughing technique in which a bulldozer was used to tow the plough was not able to properly control the ditch quality, thus producing shallower and less durable ditches than the excavator. Since the 1970s, ploughing has not been employed as a method for making forest ditches and ploughing was not used in DNM. The ditches >40 years of age are few in data but the results suggest that shallowing slows down at that age and excavator-made ditches may stabilise at a depth of 50–55 cm and plough-made ditches at a depth of 40–45 cm.

For peat thickness, a maximum value of 1.2 m was used. In the thick-peated sites, ditches were deeper than those of the same age on the sites with a shallow peat layer. This pattern was similar for original and maintained ditches, but peat thickness had a greater impact in original ditches. This result is partly explained by the forest management guidelines which recommend dredging deeper ditches for thick-peated sites (Vanhatalo et al. 2015). The random variation among forest stands was high and can be partly explained because in the state-owned forests (Metsähallitus) the ditches used are shallower than those in private lands. In shallow-peated sites, the ditches are dug in mineral soil, which is more susceptible to changes in ditch dimensions, i.e. erosion of the ditch wall and deposition of the material to the ditch bed (Silver and Joensuu 2005, Stenberg et al. 2016). On the other hand, revegetation can be slower in ditches reaching mineral soil (Holden et al. 2007).

When comparing the temporal patterns in depth of the original ditches and maintained ditches, it is turned out they are very similar (Figure 1). The excavator-cleaned ditches are similar in depths up until 20 years of age, after which they appear to be a couple of centimetres shallower than original ditches. Contrary to this, Silver and Joensuu (2005) concluded that the shallowing of cleaned ditches was faster than that of original ditches, i.e. almost 30 cm in ten years. The different results may be partly due to the differences in data coverage: the data from Silver and Joensuu (2005) are from a small area in south-west Finland while the data of this study represents drainage areas around the country. However, the model for maintained ditches also suggested that in the south, maintained ditches are somewhat shallower than in the north.

A possible reason for the continuous shallowing of maintained ditches also observed in this study may be the continued subsidence of peat due to decomposition in older drainage areas, which also makes the possibility of ditch wall erosion higher in maintained ditches than in original ditches (cf. Silver and Joensuu 2005). It should also be noted that the survey type data used in this study does not allow interpretations that are comparable to real time series: the old ditches do not represent the same population as the new ditches.

Conclusions

The general conclusion from this study is that after a quicker change in depth during the first ten years, forest drainage ditch depth decreases with increasing ditch age in an almost linear manner in old original ditches. After 35 years, the shallowing rate slightly slows down. Original ditches made by plough are 10–15 cm shallower than those made by excavator at the same age. At the age of 40 years, excavator-made ditches are 51 cm and plough-made ditches are 42 cm deep on average. In the models, ditch depth is mostly explained by ditch age. A thicker peat layer and a greater ditch bed slope generally mean deeper ditches. Cleaned ditches appeared to provide similar drainage conditions than original ditches for at least of 20 years.

The models developed in this study can be employed in anticipating the future mean depth of ditches in drained sites. In planning the future of the drained peatland area, and deciding between DNM or passive or active restoration, the information is essential. Alternatively, the average ditch depth in some specific region of interest can be estimated given that the time elapsed since ditch digging, digging method, and site characteristics are available. Because of large measurement error in ditch depth, model predictions are represented by general means surrounded by a rather wide band of confidence interval. The results also cannot show the threshold depth that would necessitate the DNM operation, because much of the site drainage condition is determined by the tree stand water use (Sarkkola et al. 2010, 2012). Ditch depth is an essential indicator for implementing DNM, but not the only one.

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