# Domination of growing-season evapotranspiration over runoff makes ditch network maintenance in mature peatland forests questionable

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## SUMMARY

In Finland, ditch network maintenance (DNM) is carried out annually on 60–70,000 ha of drained peatland to promote tree growth for forestry purposes. However, it is important to avoid ditching that contributes little to the stand growth and productivity, both to improve the economical profitability of forestry and to mitigate DNM-induced nutrient release to watercourses. We hypothesised that mature forest stands with substantial evapotranspiration potential do not necessarily need DNM, even if the ditch networks are in poor condition.

We estimated evapotranspiration (*EVT*) of forest vegetation during the growing seasons (June–September) of 2007–2011 in four forested artificial peatland catchments dominated by Scots pine stands (*Pinus sylvestris* L.) (stand volume 93–151 $m^3$ $ha^{-1}$) located in southern, western, central and northern Finland. Precipitation (P), runoff (R) and water table level (*WTL*) were monitored continuously in the field. The water storage change (ΔS) was estimated on the basis of *WTL* measurements and peat pF curves determined from *in situ* peat samples. In addition, tree stand transpiration (T) was estimated in two of the catchments using the sap flow method. *EVT* was estimated as the residual term of the water balance equation.

During the growing season, *EVT* (153–295 mm) was 49–161 % of the total accumulated P (155–368 mm), and decreased from south to north. Within each growing season, *EVT* was always largest in July or August. Tree transpiration was about 50 % of the total forest *EVT* in the two sites where it was measured directly. The mean *WTL* was at depth 36–63 cm during the growing seasons. Clear-cutting of a 100$m^3$ $ha^{-1}$ stand on one site resulted in an average rise of *WTL* by 18 cm.

The results suggested that, in the southernmost site in particular, no drainage network management would be necessary to sustain satisfactory drainage conditions for tree growth because growing-season precipitation is transferred back to the atmosphere by forest *EVT*. In the northernmost site, ditch networks were considered important in controlling drainage conditions because of the low *EVT* potential of <100 $m^3$ $ha^{-1}$ tree stands. Further research is needed to fully understand the mechanisms behind forest *EVT* potential, as one site with high tree stand volume had surprisingly low *EVT* potential.

**KEY WORDS:** drainage; Finland; *Pinus sylvestris*; water balance; water table; water use by trees

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## INTRODUCTION

In Finland, drained peatland forests (5.7 M ha) comprise about 25 % of the total forest area, and contribute a similar fraction of the total annual growth. The first systematic drainage operations intended to improve tree growth in forestry were on state-owned land in the early 20th century, but the bulk of drainage operations were carried out during the 1960s and 1970s (Päivänen & Hånell 2012). Drainage has contributed to establishing most of the currently achieved annual growth of peatland forestry, which is about 25 M $m^3$. Pristine mires are no longer claimed for new drainage, and drainage work now focuses on operations such as ditch cleaning and complementary ditching to maintain the existing ditch networks. This ditch network maintenance (DNM) is carried out on 60,000–70,000 ha annually at a cost of 15–18 M EUR $yr^{-1}$.

In order to keep the drainage conditions favourable for tree growth, forest management guidelines recommend 1–2 DNM operations during the stand rotation (Hyvän metsänhoidon …, 2007). DNM has been shown to lower the average water table during the growing season by 5–10 cm (Ahti & Päivänen 1997) and to increase tree growth (Hökkä & Kojola 2002, Kojola *et al.* 2012). However, ditching is regarded as the most harmful forestry practice from the viewpoint of water quality protection (Finér *et al.* 2010). At national scale, DNM is estimated to increase suspended sediment export by over 50 % compared to natural background loading, and to cause about two-thirds of the phosphorus export from forest areas (Finér *et al.* 2010). Furthermore, DNM creates additional management costs that may significantly affect the overall financial profitability of peatland forestry (Ahtikoski *et al.* 2008), and so should be avoided on sites where it can be expected to contribute little to stand growth and productivity.

At present, the only criterion for the timing of DNM in forestry operations is the technical condition of the ditch network, which does not indicate directly whether tree growth will be improved by DNM. For undisturbed tree growth, it is essential that the water table is below the root zone (at least 35–40 cm below the soil surface) during the late growing season (Sarkkola *et al.* 2012a), when high water table is most detrimental to tree growth and vitality (Pelkonen 1975). Long-term monitoring studies in highly stocked peatland stands have shown that the growing-season water table remains sufficiently low that DNM has no impact on tree growth, even if the drainage function of the ditches is poor (Sarkkola *et al.* 2012a); and that water table level and runoff show no clear response to DNM (Koivusalo *et al.* 2008). These findings indicate that evapotranspiration (*EVT*) may be the dominant factor controlling soil water conditions in mature forest stands on drained peatland (Heikurainen 1963, Ahti & Hökkä 2006, Sarkkola *et al.* 2010) and may even override the drainage effect of the ditch networks. Understanding the evapotranspiration of tree stands of differing volume and growth under different climatic conditions could enable the development of economically and environmentally better DNM guidelines for operational peatland forestry, in which tree stand evapotranspiration would be an additional criterion for determining DNM requirements.

The aim of the study reported here was to evaluate the growing-season water balance in drained peatland forests, and on this basis to estimate the role of water use by forest vegetation (tree stand and understory vegetation) in maintaining appropriate soil water conditions for undisturbed tree growth. It involved water balance and water flux measurements and calculation of seasonal water balances for small artificial catchments (hydrologically isolated by double-ditching) on drained forested peatlands located in climatically different parts of Finland. We hypothesise that evapotranspiration dominates over runoff in the water balance of well-stocked peatland forest during the late growing season, and is thus a key factor in determining the need for DNM.

## METHODS

### Study sites and experimental catchments

The locations of the four research sites within Finland are shown in Figure 1, and general information about them is given in Table 1. The long-term (1971–2000) mean annual temperature sums for these areas ranged from 900 to 1250 dd°C (+5 °C as the threshold value), and the annual precipitation from 500 to 650 mm of which 100–250 mm fell as snow during winter (Drebs *et al.* 2002).

The sites were drained for forestry 40–100 years ago with a ditch spacing varying from 40 to 100 m. Peat thickness at all of the sites exceeded one metre and in 2007 the total volumes of the forest stands ranged from 93 to 151 $m^3$ $ha^{-1}$, which are typical stand volumes for forests dominated by Scots pine (*Pinus sylvestris* L.) that were initially drained 40–50 years ago. The two southernmost sites (Vilppula and Tuusula) represented the dwarf-shrub site type (Vasander & Laine 2008) where the dominant understory vegetation species were *Ledum palustre*, *Vaccinium uliginosum* and *V. vitis-idaea,* and the two northernmost sites (Kannus and Rovaniemi) belonged to the more fertile *V. vitis-idaea* drained peatland site type with *V. myrtillus*, *V. vitis-idaea, Betula nana* and *Eriophorum vaginatum* as the dominant plant species.

We estimated forest evapotranspiration during a series of consecutive growing seasons in plots on drained deep peatland dominated by Scots pine. Each plot was hydrologically isolated from the surroundings by double ditching (see Hökkä *et al.* 2008), and so can be regarded as an artificial experimental catchment. The condition of the drainage ditches was either already classified as poor due to extensive vegetation occupation, or they were dammed artificially with soil embankments so that all five catchments were in need of DNM according to the present guidelines for operational forestry. We studied one or two (Vilppula) catchment plots of area 0.5–2.4 ha at each of the four sites. The plots were established 1–2 years before the water balance measurements were initiated in 2007.

### Hydrometeorological measurements and water balance calculation

Water table level (*WTL*) within the plots and runoff (*R*) at the catchment area outlet were measured during five growing seasons (2007–2011). The measurements were mostly concentrated within the frost-free period, but runoff was monitored throughout the year at Vilppula_1 and Tuusula.

A systematic grid (e.g., 10 × 15 m) of dipwells (perforated plastic tubes 120 cm long, 3.5 cm diameter) was set up and *WTL* (depth in cm below the soil surface) was measured manually at weekly or fortnightly intervals. One dipwell at the centre of each plot was also read with an automatic probe (TruTrack WT-HR500, one-hour recording interval). The dipwell grid usually covered the whole catchment plot, but at Tuusula (plot area 2.4 ha) it covered only a 30 × 40 m sub-area positioned to cover the whole water table profile between two parallel drainage ditches. At Vilppula (central Finland), *WTL* was monitored across two adjacent sub-plots, of which one (Vilppula_2) was clear-cut in winter 2009 (cutting removal 100 $m^3$ $ha^{-1}$ or 750 stems $ha^{-1}$), whilst the adjacent areas remained unmanaged (Figure 1).

Runoff was measured by recording stage in the outlet ditch immediately upstream of a V-notch weir with an automatic water height probe (30-second intervals), and making weekly or fortnightly manual observations to calibrate the automatic recordings. Runoff was not monitored at the Vilppula_2 sub-catchment (Figure 1).

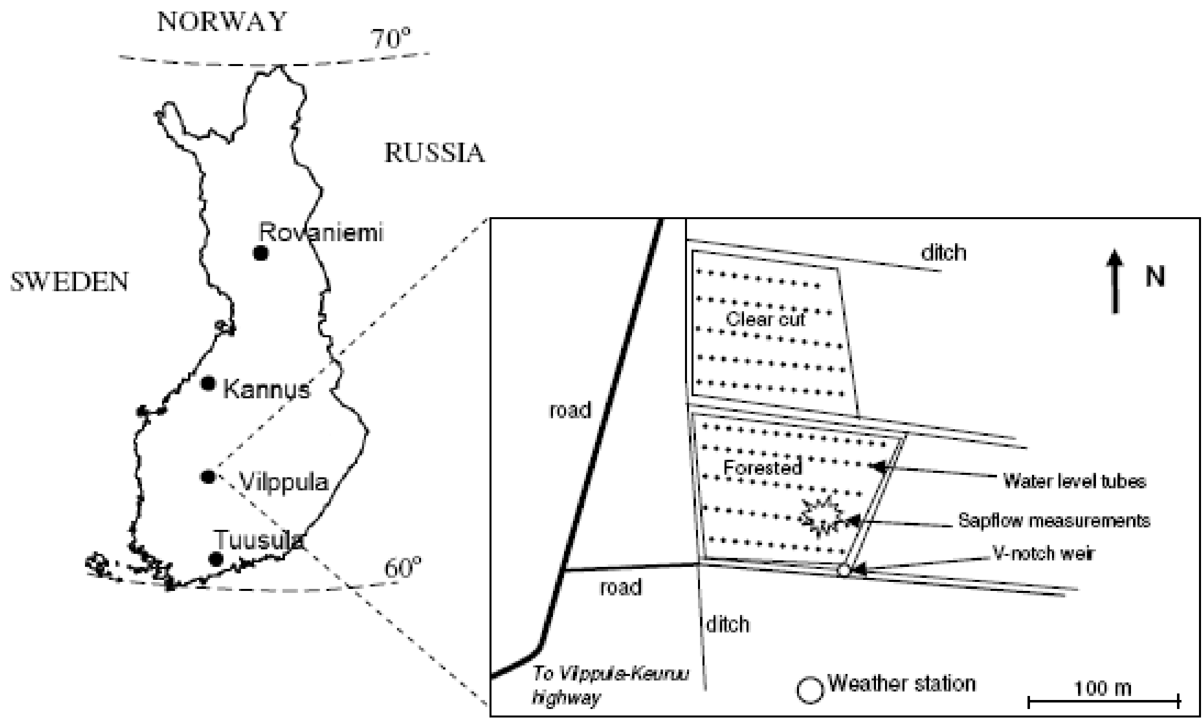


Figure 1. Map of Finland showing the locations of the research sites where experimental catchment plots were established in Scots pine stands on drained peatland. As an example of the experimental design, the schematic shows the plot at Vilppula divided into two sub-catchments (Forested = Vilppula_1, Clear cut = Vilppula_2) and the locations at which measurements were made.

Table 1. Plot, stand and climate variables of the experimental catchment sites shown in Figure 1.

| Location within Finland<br>Research site | northern<br>Rovaniemi | western<br>Kannus | central<br>Vilppula | southern<br>Tuusula |
|---|---|---|---|---|
| N-coordinate | 66° 27.3' | 63° 52.4' | 62° 3.1' | 60° 27.4' |
| E-coordinate | 26° 44.1' | 24° 19.1' | 24° 29.0' | 24° 57.2' |
| Area (ha) | 0.3 | 2.5 | 0.9 | 2.4 |
| Mean temperature 1971–2000 (°C) | 0 | 2.8 | 3.5 | 4.9 |
| Mean precipitation 1971–2000 (mm) | 537 | 500 | 601 | 650 |
| Mean temperature sum 1951–1985 (d.d.,>5°C) | 870 | 1100 | 1190 | 1276 |
| Stand volume in 2007 ($m^3$ $ha^{-1}$) | 93 | 110 | 151 | 140 |
| Ditch spacing | 23 | 40 | 100 | 30 |

At Rovaniemi and Vilppula, precipitation (*P*), air temperature and humidity, and wind speed were recorded at 10-minute intervals at a weather station in a forest clearing close to the catchment plot(s). All weather data for Tuusula and Kannus were obtained from the respective permanent weather stations operated by the Finnish Meteorological Institute at locations 10–15 km distant from the study plots. Precipitation sums and mean air temperatures for June–September in the years 2007–2011 varied between 155 mm and 358 mm and 8.2 °C and 17.0 °C (Table 2).

The change in water storage ($\Delta S$) in peat was estimated using the measured *WTL* data and site-specific water retention curves (pF) determined for three layers (0–10 cm, 10–30 cm and 30–50 cm depth) of a peat profile sample collected from the centre of each catchment plot. The uppermost layer was living mosses and forest litter, and the lower layers were actual peat; i.e., partly decomposed remains of peatland vegetation. The water retention characteristics were determined in the laboratory by measuring peat water content (cm$^3$ cm$^{-3}$) at different matric suction potentials ($\theta$, pF range 0–4). The hydraulic conductivities (*K*, m day$^{-1}$) of the 10–30 cm and 30–50 cm soil layers were estimated using the measured bulk densities of the soil samples and the equations given by Päivänen (1973) for the relationship between hydraulic conductivity and bulk density. For the uppermost (0–10 cm) litter/moss layer, the hydraulic conductivity of 0.014 m day$^{-1}$ presented by Päivänen (1973) for undecomposed peat soil was applied. The plot-specific pF curves were formed by fitting the parameters of the van Genuchten (1980) function to our water retention data. The amounts of water in the whole soil profile corresponding to distance to water table at given points in time were calculated by extracting water quantity values from the pF curve using an Excel macro specifically developed by the Finnish Forest Research Institute for calculation of water storage in soils. The daily $\Delta S$ was calculated as the difference between the actual water storage estimated for the current day and that for the previous day, and monthly $\Delta S$ was calculated by summing the daily differences.

Table 2. Precipitation sum and mean air temperature for the four-month period June–September in the years 2007–2011, and long-term averages (1974–2004), for the four research sites. The figures in parentheses show the range of monthly precipitation sums or mean temperatures (June–September) for each site/year.

| Year | 2007 | 2008 | 2009 | 2010 | 2011 | 1974–2004 |
|---|---|---|---|---|---|---|
| Precipitation sum, June–September (mm) | | | | | | |
| Rovaniemi | 267<br>(37–96) | 277<br>(34–98) | 318<br>(32–103) | 205<br>(25–79) | 209<br>(34–80) | 262<br>(8–143) |
| Kannus | 281<br>(52–111) | 358<br>(38–125) | 200<br>(19–79) | 342<br>(24–166) | 341<br>(29–118) | 212.0<br>(10–126) |
| Vilppula | 224<br>(22–105) | 310<br>(29–110) | 189<br>(38–62) | 194<br>(42–58) | 246<br>(42–108) | 280.0<br>(4–151) |
| Tuusula | 271<br>(48–123) | 274<br>(22–99) | 275<br>(37–102) | 155<br>(15–71) | 262<br>(41–86) | 264<br>(4–156) |
| Mean temperature, June–September ($^{o}$C) | | | | | | |
| Rovaniemi | 11.9<br>(6.5–14.7) | 8.2<br>(5.7–13.9) | 12.3<br>(9.1–14.7) | 11.5<br>(7.6–15.8) | 13.6<br>(9.4–17.0) | 11.5<br>(3.4–18.7) |
| Kannus | 12.8<br>(8.0–15.2) | 11.2<br>(6.8–14.1) | 12.9<br>(10.2–14.7) | 13.2<br>(8.3–19.0) | 14.7<br>(10.9–17.9) | 12.5<br>(5.4–18.4) |
| Vilppula | 13.4<br>(9.1–15.9) | 12.2<br>(7.9–15.2) | 13.3<br>(10.5–15.3) | 14.6<br>(9.7–20.4) | 15.0<br>(11.2–18.2) | 13.0<br>(5.1–19.2) |
| Tuusula | 15.3<br>(10.5–17.9) | 14.0<br>(9.8–16.9) | 15.8<br>(12.7–17.1) | 16.7<br>(11.5–22.4) | 17.0<br>(12.9–20.9) | 14.4<br>(6.6–20.3) |

The measurements of precipitation ($P$), water storage change ($\Delta S$) and runoff ($R$) were then utilised to quantify monthly $EVT$ from the forest (including tree stand and understory vegetation) during June–September 2007–2011 using the water balance equation:

$$EVT = P - R - \Delta S \quad [1]$$

For the Rovaniemi and Vilppula_1 plots, tree stand transpiration was estimated by measuring the tree-level transpiration during June–August with Granier type (Granier 1985) sap flow sensors installed in 5–8 sample trees. Sap flow rate was averaged at ten-minute intervals and recorded by data loggers. The measured sap flow rates were then up-scaled to quantify tree stand transpiration for the entire plot area on the basis of sapwood area determined from ten sample trees (e.g. Cermak *et al.* 2004). Due to failure of some of the sap flow measurements, we used data from only four summer periods (2007, 2008, 2010 and 2011) for Rovaniemi, and from two (2010 and 2011) for Vilppula.

The effects of tree stand $EVT$ on $WTL$ were demonstrated by comparing average monthly water table levels derived from the continuous $WTL$ measurements in the clear-cut and forested plots at Vilppula for the period 2007–2011. $WTL$ was monitored for two years (2007–2008) before cutting and three years (2009–2011) afterwards, and the change in water table level ($\Delta WTL$) associated with clear cutting was calculated using calibration period-control area methods (Scott 1999, Joensuu *et al.* 2002). First, we derived the linear relationship between mean daily $WTL$ in the unmanaged forested *(F)* plot (Vilppula_1) and the treatment *(CC)* plot (Vilppula_2) for the 2007–2008 period before *(B)* clear cutting:

$$WTL_{CC(B)} = \beta\left(WTL_{F(B)}\right) + \varepsilon \quad [2]$$

where $WTL_{CC(B)}$ and $WTL_{F(B)}$ are the mean daily water table depths in the treatment and control plots, respectively, before clear cutting; $\beta$ is the regression coefficient; and $\varepsilon$ is the random error. Then, the average change in growing-season water table level due to clear-cutting ($\Delta WTL_{CC}$) was calculated for the growing seasons of 2009–2011 as follows:

$$\Delta WTL_{CC} = \sum_{1}^{m}\left(\frac{\sum_{1}^{n_m}\left[WTL_{CC(A)} - \left(\beta \times WTL_{F(A)}\right)\right]}{n_m}\right) \times \frac{1}{m} \quad [3]$$

where $WTL_{CC(A)}$ is mean daily water table depth in the treatment plot after clear-cutting, $WTL_{F(A)}$ is the mean daily water table depth in the unmanaged forest plot after clear-cutting of the treatment plot, and $n_m$ is the number of days in growing season $m$.

## RESULTS

The estimated growing season (June–September) $EVT$ varied between 42 % and 161 % of total annual precipitation (155–358 mm) and increased from the northernmost to the southernmost site (Figure 2). Within each season, $EVT$ was always highest in July or August (Figure 3). The mean $EVT$ over the five growing seasons was 58 % of total precipitation (155 mm) in the northernmost catchment plot, and 122 % (297 mm) in the southernmost plot. The fraction of total growing-season precipitation discharged as runoff varied between 6 % and 44 % (15–117 mm), and was lowest in the southernmost site which had the largest stand volume (Table 3). The average change in water storage over the five growing seasons was largest in the southernmost (Tuusula) catchment, in both relative (-22 %) and absolute (-43 mm) terms. At the other sites, the average growing-season $\Delta S$ varied between -3.5 mm and +11 mm, or between -0.8 % and 5.6 % of total precipitation. At Vilppula, Kannus and Rovaniemi, average net monthly growing-season $\Delta S$ was negative if September data were excluded (Figure 3).

According to the tree sap flow measurements, growing-season transpiration was 54–66 mm at Rovaniemi (northern Finland) and 85–103 mm at Vilppula (central Finland) (Table 4), accounting for 39–48 % of the total forest vegetation $EVT$ which, in turn, was the sum of transpiration and evaporation of the tree stand and understory vegetation, and calculated as the residual term of the water balance equation (Equation 1).

Mean monthly $WTL$ during the growing season across all five monitoring years and all four sites varied between 36 and 63 cm below the ground surface, and was deepest in August. The difference in $WTL$ between the sites was larger than the inter-seasonal variation, and the water table was deeper in the southern (Tuusula) and western (Kannus) plots than in the experimental catchments in central (Vilppula) and northern (Rovaniemi) Finland (Figure 4). The deepest mean monthly $WTL$ values were mostly observed in July and August. In the Vilppula_2 catchment, the average growing-season $WTL$ in 2009–2011 (after clear cutting had been carried out) varied between 12 and 37 cm, and the average change relative to the forested Vilppula_1 plot (Equation 3) was about 18 cm. This change in $WTL$ corresponds to an increase in water storage of about 58 mm.

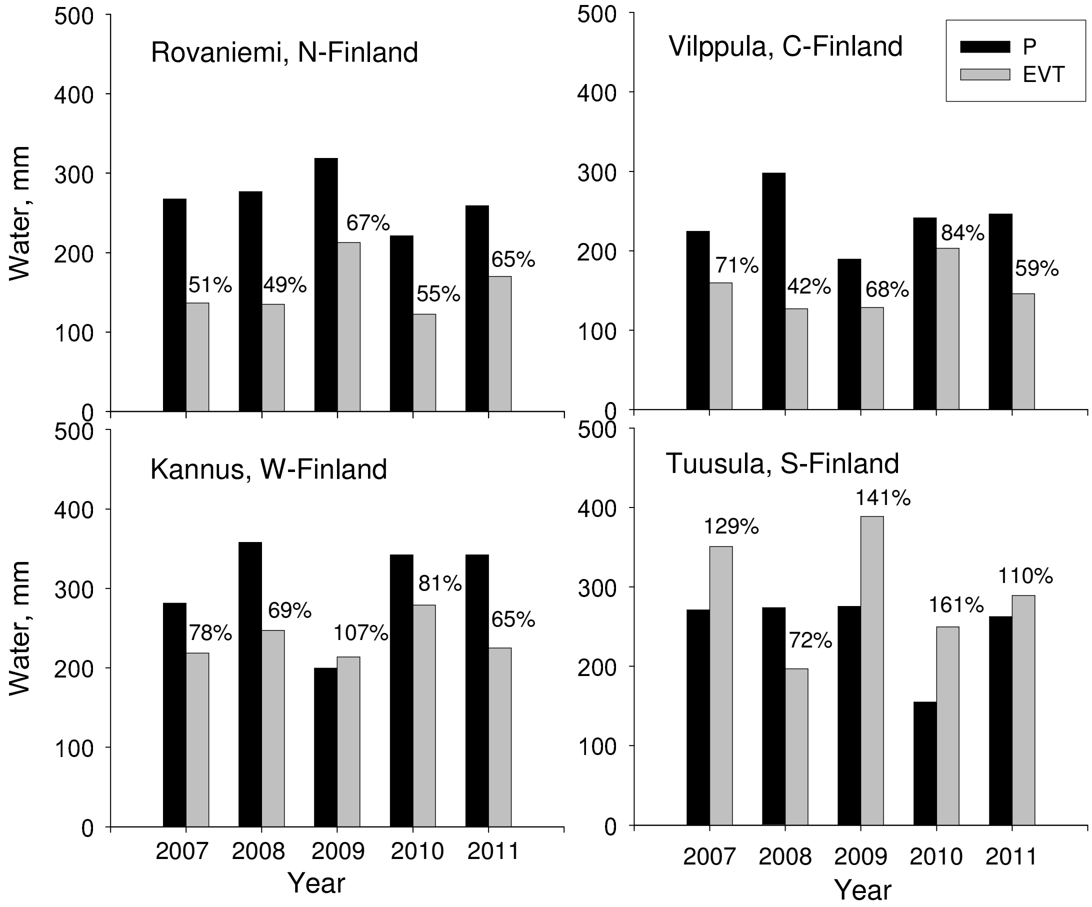


Figure 2. Total precipitation (*P*) (see also Table 1) and evapotranspiration (*EVT*) at the four experimental catchments during the four-month period June–September in the five years 2007–2011. The percentages show the proportion of total *P* accounted for by *EVT* during each period.

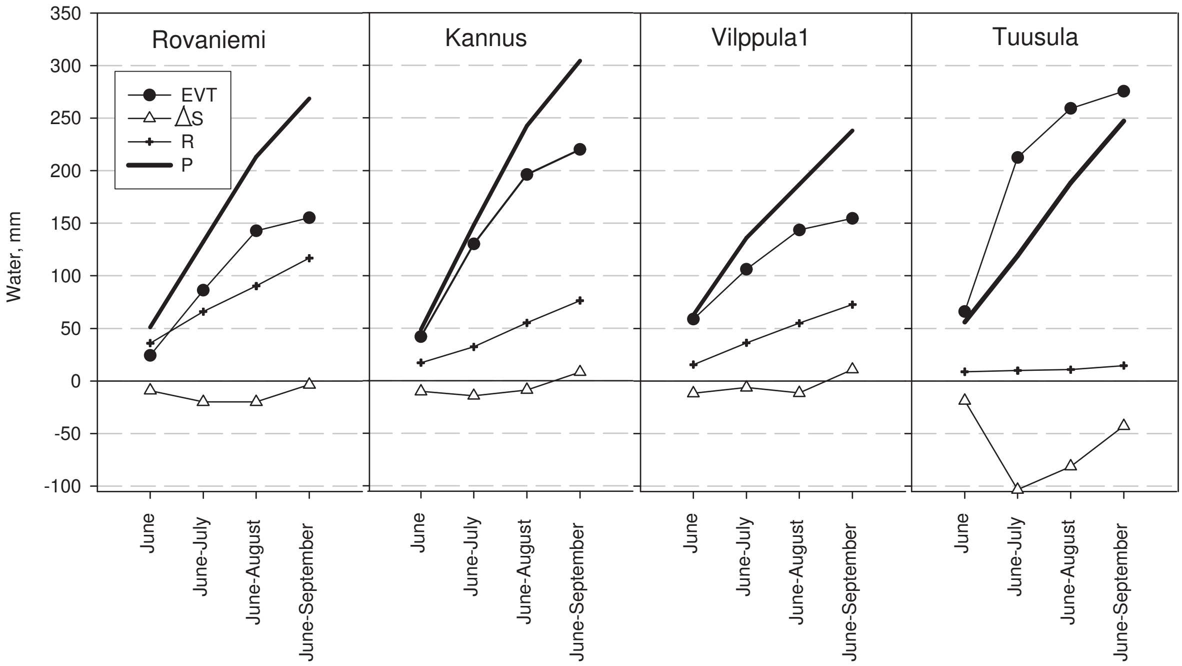


Figure 3. Accumulated monthly average (2007–2011) values of total precipitation (*P*), evapotranspiration (*EVT*), runoff (*R*), and soil-water storage change ($\Delta S$) for the experimental catchments, June–September.

Table 3. Mean (2007–2011) growing-season (June–September) precipitation (*P*), runoff (*R*), change in soil water storage ($\Delta S$) and total forest evapotranspiration (*EVT*) in the four experimental catchments.

| Catchment | Location | *P* (mm) | *R* (mm) | $\Delta S$ (mm) | *EVT* (mm) |
|---|---|---|---|---|---|
| Rovaniemi | N-Finland | 269 | 117 | -3 | 155 |
| Kannus | W-Finland | 305 | 76 | -8 | 237 |
| Vilppula | C-Finland | 240 | 76 | 11 | 153 |
| Tuusula | S-Finland | 247 | 15 | -62 | 295 |

Table 4. Total summer (June–August) evapotranspiration (*EVT*) and forest stand transpiration (*T*) for the experimental catchments in northern (Rovaniemi) and central (Vilppula) Finland.

| Catchment | Year | *EVT* (mm) | *T* (mm) | *T*/*EVT* (%) |
|---|---|---|---|---|
| Rovaniemi | 2007 | 136.2 | 65.5 | 48 |
| | 2008 | 139.4 | 54.0 | 39 |
| | 2010 | 124.2 | 58.0 | 47 |
| | 2011 | 153.2 | 64.2 | 42 |
| Vilppula | 2010 | 230.4 | 102.5 | 44 |
| | 2011 | 179.4 | 84.9 | 47 |

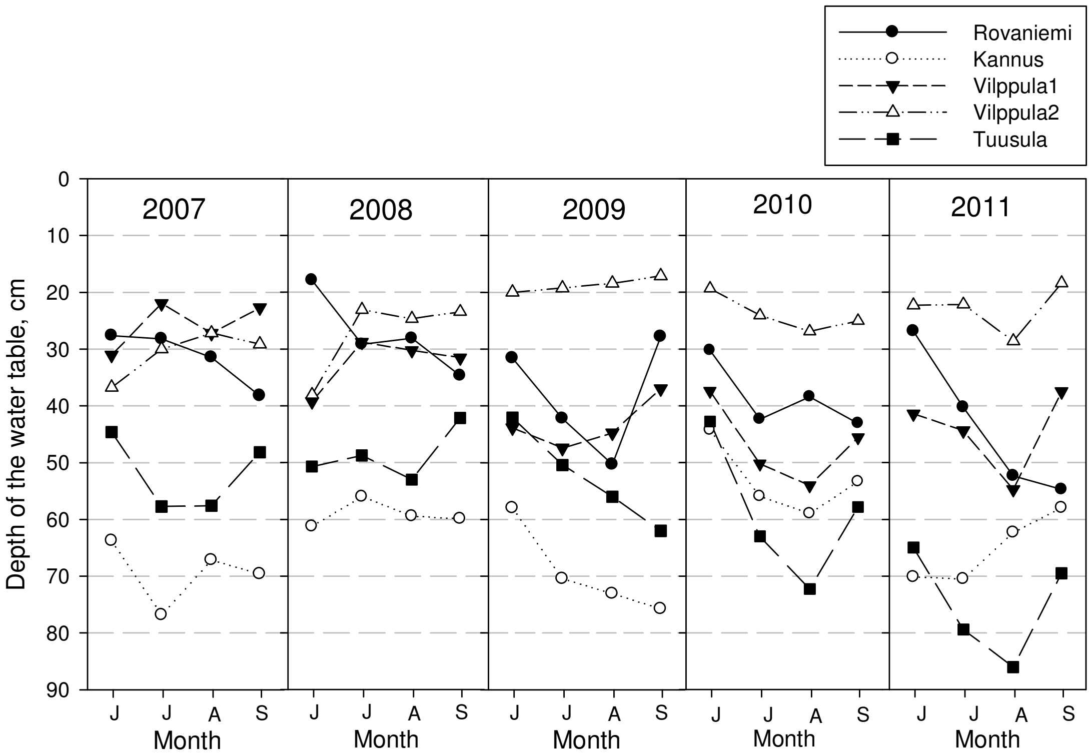


Figure 4. Average monthly water table depth (cm) in the experimental catchments in 2007–2011, derived from continuous records. The Vilppula_2 sub-catchment was clear-cut in winter 2009; otherwise, no treatments were applied to any of the stands.

## DISCUSSION

Monitoring of the water balance components in drained peatland forests over five years showed that, in northern Finland, the total growing-season (June–September) *EVT* (~150 mm) was about half the total precipitation during the same period, and total runoff was of the same magnitude as *EVT*. In the southernmost site, the total growing-season *EVT* exceeded the growing-season precipitation, so that runoff was a negligible component of the site´s water balance during this part of the year. The excess of *EVT* over precipitation was reflected by lowering of the water table and a decrease in soil water storage towards the end of the growing season.

Because the total forest evapotranspiration and the tree stand transpiration (derived from sap flow measurements) decreased towards the more humid and cooler northern conditions, the ditch network became more significant in controlling drainage conditions (runoff). The sap flow measurements at both the southern (Vilppula) and the northern (Rovaniemi) site indicated that tree stand transpiration was about half of the total forest *EVT*, meaning that tree stand interception and understory vegetation *EVT* accounted for the other half of the total forest *EVT*. Ilvesniemi *et al.* (2010) measured the ten-year water balance of a 120 $m^3$ $ha^{-1}$ Scots pine stand growing on mineral soil at the Hyytiälä SMEAR station, which is located about 30 km south-west of our plots at Vilppula. They estimated that the mean annual total forest *EVT* amounted to 425 mm, of which about 75 % occurred during the period June–September. *EVT* exceeded precipitation under late-summer conditions, and this was also the case in our study. Gardenäs & Jansson (1995) studied the water balance of Scots pine stands in Sweden and reported that the total annual forest *EVT* was 320–580 mm depending on the geographical location of the site and the stand leaf area index. Jarosz *et al.* (2008) studied a mature planted maritime pine (*Pinus pinaster*) stand in France (height: 12–20 m, 410 stems $ha^{-1}$) and found that the June–September tree stand transpiration was about 150 mm. Except on the southernmost Tuusula plot, our total forest *EVT* and tree stand transpiration estimates are low compared with the results of these earlier studies, possibly reflecting the relatively low timber production capacity of the peatland sites that we studied. The trees in the Vilppula_1 plot had also suffered from the fungal disease Scleroderris cancer (*Gremmeniella abietina*) during an epidemic and, consequently, the average spread of the living canopy was only about 30 % of the height of the trees, compared with 45–53 % at the other sites. Furthermore, the Vilppula stand showed clear symptoms of nutrient deficiency. These factors could explain why *EVT* was lower at Vilppula than might be expected on the basis of its larger tree stand volume (151 $m^3$ $ha^{-1}$ *versus* 93 $m^3$ $ha^{-1}$) and more favourable climatic conditions compared to the northern Rovaniemi site.

A possible explanation for the low ratio of tree stand transpiration to total forest *EVT* (39–48 %) in our sites is that the evapotranspiration of the understory vegetation, which consists of abundant and vigorous dwarf shrubs (e.g. *Ledum palustre*), is higher than understory vegetation *EVT* in, for example, mineral soil forests. Launiainen (2010) reports that the contribution of understory vegetation to total forest *EVT* in mature boreal Scots pine stands on upland sites varies between 18 % and 25 %; whilst Iida *et al.* (2009) give a range of 10–60 % for boreal forests, depending on the leaf area and the density of the overstory tree stand. In peatlands drained for forestry, the evapotranspiration capacity of understory vegetation increases considerably as the hydroseral succession proceeds (Laine 1984), but its contribution to the total forest *EVT* is not fully understood. However, our relatively sparse study stands of Scots pine growing on dwarf-shrub covered peatland probably created conditions with exceptionally high understory vegetation *EVT*.

It was not possible to investigate the role of canopy interception in this study, but Smolander *et al.* (2012) report that, in 2007–2010, summer-time interception at the (northernmost) Rovaniemi catchment plot of the present study was 17–21 % of precipitation. These data agree well with results obtained elsewhere by Päivänen (1966), who studied the distribution of rainfall in Scots pine stands on drained peatlands and estimated that the canopy interception across three growing seasons varied between 7 % and 32 % of precipitation, depending on the stand volume (10–237 $m^3$ $ha^{-1}$) and canopy coverage (7–38 %).

In the catchment plots at Tuusula and Kannus, the mean water table level in late summer was at 35–40 cm depth, which has been regarded as the minimum depth at which the trees would not suffer from excessive wetness and anoxic conditions (e.g. Sarkkola *et al.* 2012a). At Rovaniemi, mean monthly water table depth was less than 30 cm at least once during the growing season of every year, implying a need for DNM. Clear-cutting of the Vilppula_2 sub-plot clearly raised the water level above 30 cm depth, and the change was persistent for three years after clear-cutting. The post-treatment rise in *WTL per* removed stand volume (100 $m^3$ $ha^{-1}$) is in accordance with earlier observations on drained peatland pine stands in Finland (Heikurainen 1967, Heikurainen & Päivänen 1970, Päivänen 1982), as well as with results from black spruce stands on peatland in Canada (Dube *et al.* 1995, Jutras & Plamondon 2005). In Sweden, Lundin (1999) reported a maximum rise of 17 cm in mean water table level during the four years after clear-cutting of a 300–400 $m^3$ $ha^{-1}$ Norway spruce stand. In general, the rise of the water table after clear-cutting seems to be so great that it may be harmful to tree growth (e.g., Heikurainen & Päivänen 1970, Dube *et al.* 1995). Thus, it may be necessary to pay attention to the condition of drainage network after a significant change in standing crop volume.

Overall, our experimental stands represented the most typical drained peatlands in Finland, where about 70 % of the peatland forests are Scots pine stands in their commercial thinning phase (Päivänen & Hånell 2012). In the present study, hydro-meteorological factors were monitored across a large climatic range and during both exceptionally rainy years and warm, dry growing seasons. Thus, the data should convey well the effects of variation in weather conditions across the whole geographical range of drained Scots pine stands in Finland.

Because *EVT* was derived by indirect estimation as the residual term of the water balance equation, the *EVT* data incorporate any errors in the measurements of runoff, precipitation and water storage change. In catchment plots that are isolated from their surroundings by double ditching, there is always a risk of incomplete hydrological isolation, which would introduce errors in the runoff estimates (Koivusalo *et al.* 2008). The calculations of water retention characteristics were based on a single point sample from the centre of each catchment plot, and the spatial variation in water retention properties remains unknown. For these reasons, further research is needed to understand the mechanisms behind forest *EVT* potential, particularly in the Vilppula site where high tree stand volume resulted in surprisingly low *EVT*.

Given the uncertainties in the estimation of water balance components we conclude that, in mature peatland stands and particularly in southernmost Finland, *EVT* during the growing season may substantially exceed precipitation over the same period, thus keeping late summer water table levels sufficiently low for undisturbed tree growth (Sarkkola *et al*. 2012*a*). Consequently, there is no need for DNM, even if the condition of the ditch network is poor. In contrast, in low-stocked and poorly growing stands, especially in northern Finland, the forest *EVT* may be low and the site drainage conditions regulated mostly by runoff, so that DNM may be necessary where the ditches have lost their water conduction capacity.

At present, the only criterion for the timing of DNM in operational forestry is the condition of ditch networks, but our results show that the *EVT* of forest vegetation may override the drainage effect of ditch networks. Future research should emphasise the use of advanced hydrological modelling in combination with empirical case studies to understand more profoundly the mechanisms behind peatland forest *EVT* potential (e.g. Koivusalo *et al.* 2008, Schwärzel *et al.*, 2006).

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