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Partitioning forest evapotranspiration: Interception evaporation and the impact of canopy structure, local and regional advection

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SUMMARY

Spatial and temporal variation in interception evaporation, energy balance during rain and total water loss was explored in a structurally heterogeneous Norway spruce [*Picea abies* (L.) H. Karst.] plantation in western Denmark. The trees are arranged in a distinctive small scale mosaic (0.25 ha) of young open canopy stands interspaced with older mature closed canopy stands. The mature stands are bound by a single line of taller Grand Fir [*Abies grandis*] on their northern edge. Interception loss (I) was measured and modeled in the open and closed canopy stands and under a Grand Fir row using net precipitation gauges and the Gash rain interception model. Incorporating complementary data on individual stand transpiration, forest floor evaporation and total ET (Ringgaard et al., 2012) we show that (a) I is 3% points higher in the closed canopy than in the open canopy (34% and 31% of P_G respectively) while the Grand Fir row promotes a zone of relative drought with $I = 47\%$, (b) in terms of total water loss, the open canopy has an annual ET of about 7.5% higher than the closed canopy stand and (c) in months with little precipitation there is good agreement between the individual components of the evaporation balance and the gap-filled eddy-covariance evapotranspiration (EC-ET) estimate while in months with high precipitation the EC-ET data underestimate both the magnitude and variability of I. The Gash model had to be parameterized separately for summer and winter. In winter, the available energy for evaporation during rain was dominated by regional scale advection of heat from the North Sea, while in summer half the available energy came from local advection. The mean evaporation rate during rain was 0.09 mm h^{-1} in winter and 0.21 mm h^{-1} in summer.

1. Introduction

Interception loss (I) from forested areas is an important part of the catchment water balance. Following afforestation catchment yields show a strong decrease primarily due to the increase in I (Law, 1957; Sahin and Hall, 1996). I varies strongly with forest structure, forest size and climate (Herbst et al., 2006, 2007, 2008). In humid, temperate climates such as Northwestern Europe I expressed as a percentage of gross precipitation (P_G) often falls within the range of 30–40% for coniferous forests (Johnson, 1990; Rosenqvist et al., 2010). Large seasonal and annual variation has been observed, however, due to variation in weather patterns (Gash et al., 1980).

Several models have been developed to estimate I_{loss} (e.g. Rutter et al., 1971; Gash, 1979; Calder, 1986; Gash et al., 1995). The most widely and successfully used model is that of Gash (1979) which is driven by daily rainfall data and requires site specific parameters such as the mean evaporation rate ($\overline{E}$) and mean rainfall rate ($\overline{R}$) during saturated conditions and canopy structure parameters such as the proportion of free throughfall (p) and the canopy water storage capacity (S). A reformulated model version (Gash et al., 1995) has shown superior results for forests with incomplete canopy cover and should be preferred over the original model. The saturated conditions from which $\overline{E}$ and $\overline{R}$ are derived are in most cases not determined by actual measurements of canopy wetness, but assumed to be those hours where P_G is above a certain threshold, typically $\geqslant 0.5$ mm h^{-1} (Gash, 1979; Deguchi et al., 2006; Herbst et al., 2008). This is done for practical purposes, although being technically incorrect since a forest canopy, once wetted, can stay wet even during short rainless periods within a precipitation event (e.g. Pearce and Rowe, 1981). $\overline{E}$ is usually estimated through the application of the Penman–Monteith formula (PME) (Gash, 1979; Gash et al., 1980, 1995) with the surface resistance set to zero. More recently use of the energy balance and an eddy-covariance

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(EC) based estimate of the sensible heat flux has also been tested (Gash et al., 1999; van der Tol et al., 2003; Herbst et al., 2008). Both methods make use of meteorological measurements which are one dimensional in nature, making them ill-suited to capture lateral advection of energy which appears to occur in forests during rain, according to energy balance considerations (Shuttleworth and Calder, 1979; Ringgaard et al., 2011; Carlyle-Moses and Gash, 2011).

The Gash model has been successfully used over a wide range of climates and on a wide range of forest types, e.g. a northern hardwood in Canada (Carlyle-Moses and Price, 1999), a thornscrub in north-eastern Mexico (Návar et al., 1999), the Amazonian rain forest (Lloyd et al., 1988), coniferous forests in Great Britain (Gash et al., 1980), a mixed deciduous woodland in England (Herbst et al., 2008) and hedgerows in southern England (Herbst et al., 2006). However, Carlyle-Moses and Gash (2011) identified some important remaining uncertainties in the modeling of rainfall interception and called for more studies focussing on advection being an important energy source and on three-dimensional stand-structure and its influence on the magnitude of I. The present study was motivated by these knowledge gaps and features a Norway spruce plantation with a distinctive small-scale (0.25 ha) alternating pattern of stands with different ages and heights. By employing separate measurements of net precipitation in each stand type we investigated the following questions:

1. Does the complicated canopy structure in Gludsted plantation give rise to spatial variation in I and what is the impact on total ET?
    a. Can upscaled I be validated at the forest scale by independent measurements of tree transpiration, forest floor evaporation and EC-evapotranspiration?
2. What are the main drivers of temporal variability in interception evaporation and, specifically, what is the role of advection?
    a. To what extent is advection captured by 1D meteorological measurements?
3. Is the Gash model able to estimate total forest interception and if yes:
    a. What is the impact on modeled I of different methods for indentifying saturated canopy conditions?
    b. What is the impact of the mean E estimation method?

2. Materials and methods

2.1. Research site

The experiment was carried out in Gludsted Plantation in the central part of Jutland, Denmark (56°4.4′N, 9°20.1′E). The plantation was established about 100 years ago, and is today one of the largest forested areas in Denmark (3500 ha). The climate can be characterized as maritime, with a mean annual temperature of 8 °C and an annual precipitation of 850 mm. The weather is dominated by prevailing westerlies from the Atlantic Ocean and the accompanying wandering cyclones. The site is located on a flat outwash plain from the last glaciation. The plantation consists mainly of Norway spruce [*Picea abies* (L.) H. Karst.] arranged in a distinctive checkerboard pattern with the size of individual squares being approx. 0.25 ha (Fig. 1). The age of the stands ranges between 12 and 45 years, but a general grouping of "young" stands aged approx 20 years and "mature" stands aged approx. 40 years can be identified. The young and mature stands are arranged in strips oriented east–west with a typical repeated north–south pattern of young–mature–young–mature or young–mature–mature–young. The mature stands are bound on their northern edge by a single row of Grand Fir [*Abies grandis* (Douglas ex D. Don) Lindl.]. Within each stand the trees are planted in rows, most of which have a distance of 1.8 m between them, apart from rows next to access tracks (Ringgaard et al., 2012).

The young Norway spruce stands have an open canopy structure. Green needles extend to within a few meters of the forest floor in many places, and small patches of forest floor are visible from the sky. The mature Norway spruce stands have a closed canopy structure. The living crowns are firmly separated from the ground and the forest floor is completely shaded. The typical tree heights are 15 m for the young Norway spruce stands, 20 m for the mature Norway spruce stands and 25 m for the Grand Fir rows. The number of trees per unit ground area is 30% higher in the young stands than in the mature stands, while at the same time the basal area is 30% less in the young stands due to a smaller average tree size (Table 1).

2.2. Gross precipitation

P_G was measured using a heated tipping bucket rain gauge (Rimco 7499, McVan Instruments, Mulgrave, VIC, Australia) installed atop the instrument hut in the center of a small clearing. Height angles from the horizontal plane of the tipping bucket gauge to the top of the surrounding trees averaged 35°. According to Vejen (2005) height angles of more than 30° do not require any correction due to loss of precipitation from locally increased turbulence across the gauge orifice. In practice, Herbst et al. (2007) found that the rain shadow from an approx. 15 m high canopy in Wytham Woods, UK, had a horizontal extent of about one half the canopy height. The climate in central UK and Denmark is comparable in terms of storminess and precipitation patterns, which suggests that loss due to rain shadow only becomes significant at height angles of more than 60° ($\arctan(h/(0.5 \cdot h)) = \arctan(2) = 63°$) for liquid precipitation. The measurements of P_G were compared with the distance weighted average precipitation of the nearby standard gauges run by the Danish meteorological institute (Sharling, 1999). Good agreement was observed on annual precipitation sums (<5% difference) and no systematic bias was observed on monthly sums.

2.3. Throughfall

Throughfall was measured using two separate gauge systems. Three troughs made up of 110 mm wide and 4.11 m long plastic guttering where attached to automatic rain gauges (ARG100). Each trough had a surface area corresponding roughly to nine ARG100 rain gauges, yielding a sensitivity of 0.028 mm/tip. The guttering was mounted on a wooden framework at an inclination of about 10% to promote drainage to the rain gauge. Each trough represented one stand type and all troughs were placed perpendicular to the orientation of the tree rows. In this setup they covered about two crown dimensions and thus captured most of the systematic spatial variability of the throughfall caused by the regular pattern in canopy structure. This assumption was confirmed statistically by calculating the semivariance of the throughfall totals captured by the manual gauges (see below) for various distances. There was no increase in semivariance beyond a distance of 2.6 m (data not shown). A second system consisted of 14 simple storage gauges made from 2 to l soda bottles ($D = 10$ cm) with the narrow top cut off. The bottles were placed along a transect covering all three stand types with an average distance of 2.6 m between neighboring bottles. According to Lloyd and Marques Filho (1988) fixed throughfall gauges represent the spatial variability of throughfall better when arranged in a line rather than in a grid. When more than a week had passed between the reading of the gauges and the last rainfall the data were rejected because potential catch loss due to evaporation would no longer be negligible. The guttering