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Changes in soil water balance following afforestation of former arable soils in Denmark as evaluated using the DAISY model

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SUMMARY

Land use change alters water and element cycles, but the changes in these cycles after conversion, for example, from cropland to forest are not fully described in hydrological and nutrient transport models, which usually describe either cropland or forest stands. In the European Union future afforestation is likely to occur on abandoned cropland, and evaluation of the future impacts of this land use change will require projections with models that include combined cropland-forest modules. This study used the agro-based DAISY model (Version 4.93) to investigate changes in the soil water balance over four decades following afforestation of a homogeneous area of former arable land on a sandy loam in Denmark. Hydrological data collected during nine hydrological years (April 2001–March 2010) were used to test the DAISY model. Monthly data on soil water content at 0–90 cm used for calibration were available from April 2001 to December 2002 for six monoculture stands of oak (age 8, 22 and 31 years) and Norway spruce (age 4, 13 and 32 years). Model performance was evaluated by considering uncertainties in model inputs using the Generalised Likelihood Uncertainty Estimation (GLUE) procedure. The GLUE estimates obtained (uncertainty bands 5% and 95%) agreed satisfactorily with measured monthly soil water content during the calibration period (April 2001–December 2002). Similarly, in the oldest oak stand, long-term monitoring observations and predictions of monthly water content were in satisfactory agreement during the period January 2003–March 2010). Sensitivity analysis showed that the DAISY model was most sensitive to the potential evapotranspiration factor and soil hydraulic parameters included in the Campbell model. Simulation results during nine hydrological years showed that 16–25% of incoming precipitation led to water recharge in the spruce stands, while the corresponding range for oak stands was 25–27%. A 35-year DAISY simulation revealed that Norway spruce consumed more water than oak, with differences in annual water recharge in the range 31–174 mm year^{-1} and with greater differences in rainy years (precipitation >900 mm year^{-1}).

1. Introduction

During coming decades, it is expected that the European Union will face a reduction in agricultural area and a conversion of abandoned cropland into forest (Rabbinge and van Diepen, 2000; Rounsevell et al., 2006; Heil et al., 2007). In Denmark, a parliament resolution call for a doubling of the forest area and the current National Action Plan for the Aquatic Environment III recommends afforestation of arable land as a measure to reduce nitrogen (N) and phosphorus (P) pollution from diffuse sources (Grant et al., 2006). In addition, Madsen (2002) noted that the objective of afforestation of the Danish countryside has changed from providing an alternative to agriculture on marginal agricultural land to providing a means for securing environmental and recreational purposes.

There is strong evidence that afforestation of abandoned cropland has a direct impact on the water balance, affecting evapotranspiration and subsequently groundwater recharge (Sahin and Hall, 1996; Farley et al., 2005; Brown et al., 2005; Nosetto et al., 2005; Verstraeten et al., 2005). This is partly due to increased canopy interception compared with cropland. A particularly important factor is the composition of the vegetation cover. Some studies indicate that water recharge is lower in Norway spruce than in oak stands, a finding mainly attributed to higher interception evaporation losses in spruce stands compared with oak (van der Salm et al., 2007; Rosenqvist et al., 2010).

The development of computer simulation models has provided methods to explain how changing land use affects hydrological

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fluxes. A number of forest models are available to predict soil water dynamics, ranging from simple regression models to complex process-based models, such as those presented in comprehensive reviews by Porté and Bartelink (2002), van der Salm et al. (2004) and Muzylo et al. (2009). Some of these forest models and other hydrological models have been used to evaluate the effects on the water balance of converting cropland to forest throughout the world. These include INCA (Bastrup-Birk and Gundersen, 2004), AFFOREST sDSS (Gilliams et al., 2005), Wave (Verstraeten et al., 2005), CoupModel (Christiansen et al., 2006, 2010), SWAT (von Stackelberg et al., 2007), SWIM (Wattenbach et al., 2007), SEBAL (Zhang et al., 2008) and SWAP (van der Salm et al., 2007; Rosenqvist et al., 2010).

Understanding the water balance in the soil is the first step in determining how the soil water flow affects the leaching of chemicals from agricultural, forest and natural areas. In Denmark, this has led to the development of the DAISY model (Hansen et al., 1990; Abrahamsen and Hansen, 2000). It is a mechanistic one-dimensional agro-ecosystem model that offers a detailed description of water balance in agricultural systems, which considers soil water dynamics, snow accumulation and melting, interception by canopy, infiltration and ponding, soil evaporation and transpiration. The DAISY model has been successfully tested under a wide range of soil, crop and climatological conditions (e.g. Hansen et al., 1991; Svendsen et al., 1995; Jensen et al., 1997; Kröbel et al., 2010), with several evaluations in Denmark (e.g. Jensen et al., 1994, 1996; Bruun et al., 2003). DAISY has also been updated to include further modules for simulation of N and carbon (C) dynamics in agro-ecosystems, intercropping systems, and the fate of pesticides. Furthermore, the model has an option for working in a distributed mode simulating multiple soil columns and it is also possible to link the DAISY model to the distributed hydrological catchment model MIKE/SHE with the help of Geographic Information Systems (GIS). For example, Boegh et al. (2009) used the DAISYGIS version for simulations of water balance at large scale, which included agricultural and forest areas. The latter is the only application of the DAISY model to forest areas, but at large spatial scale.

One limitation of some hydrological models is the large amount of input variables and parameters necessary. In particular, the use of such models to date has been limited by the lack of site-specific input parameters for hydraulic soil properties, such as soil water characteristics, and unsaturated and saturated hydraulic conductivity (Lilly et al., 2008). Alternate methods for input derivation are needed. Thus, the estimation of hydraulic soil properties in hydrological modelling is usually based either on physical models or empirical models developed from existing soil databases, which are commonly named pedotransfer functions. One of the most widely applied physical models is that presented by Campbell (1974). It uses an analogy of average pore radius distribution to water content relations based on capillary concepts and has been used in several soil water modelling applications, e.g. Wagner et al., 1998; Poulsen et al., 2002; Kawamoto et al., 2006.

Beier (1998) noted that when modelling water fluxes in forest there are important sources of uncertainty that should be considered, such as soil spatial variability in hydraulic properties, differences in tree growth, canopy parameters used to calculate evapotranspiration and variability in plant parameters between different subareas. In this sense, the equifinality concept recognises that under the limited measurements available in any application of an environmental model, it should be accepted that there are many different model structures and parameter sets that can be used in simulating the available data (Beven, 2008). Based on the equifinality concept, Beven and Binley (1992) proposed the Generalised Likelihood Uncertainty Estimation (GLUE) methodology for calibration and uncertainty estimation of models. Although the GLUE methodology has mainly been used to calibrate and perform uncertainty analysis on a variety of hydrological models, it has also been used in a wide range of environmental modelling applications (e.g. Schulz and Beven, 2003; Piñol et al., 2005; Cameron, 2006; Hansson and Lundin, 2006; Salazar et al., 2011).

In the present study, the DAISY model was used to investigate changes in soil water balance over time following afforestation of a former arable soil (sandy loam) in Denmark using soil moisture measurement from six forest stands (two forest types at three stages of stand development) and climate data from nine hydrological years (April 2001–March 2010). Specific objectives were: (i) to test the applicability of the agro-based DAISY model in simulating water balance in afforested stands; (ii) to evaluate the performance of the model by considering the uncertainties in model inputs using the GLUE methodology, in particular the performance of the Campbell's hydraulic conductivity model; iii) to carry out a sensitivity analysis using the GLUE results; and (iv) to assess the effects of oak and Norway spruce on the change in water balance using long-term Daisy simulations (35 years).

2. Materials and methods

2.1. Site description and measurements

A new forest area was designated at Vestskoven and the first forest stands were established in 1967. Vestskoven is situated 15 km west of Copenhagen, Denmark (55°41′N, 12°21′E, altitude 20–28 m a.s.l.). Tree seedlings have been successively planted on arable land from 1967 onwards and today new forest stands are still being continuously established. For the present study, three stands of common oak (*Quercus robur* L.) (planted 1993, 1979 and 1970) and three stands of Norway spruce (*Picea abies* (Karst.) L.) (planted 1997, 1988 and 1969) were selected to represent chronosequences ranging from 4 to 32 years since afforestation. These stands were denoted VO93, VO79 and VO70, and VS97, VS88 and VS69 (V for Vestskoven, O for oak, S for spruce, and the year of planting). All stands were located within a $1 \times 3\ \mathrm{km}^2$ area in the Vestskoven forest and it was verified for each stand that the land use had been agriculture or horticulture for centuries before afforestation. The trees were planted in rows at 2.5 m distance to allow for some mechanical control of weeds that would otherwise delay establishment or survival of the trees on the agricultural fields. The stands were thinned regularly after canopy closure according to the common management practice of the forest district. Stand characteristics measured in June 2001 and some vegetation variables are shown in Table 1. A detailed description of the area, forest stands, soil chemistry, management practices and measurements carried out during the period 2000–2005 in the forest chronosequences is presented in Vesterdal et al. (2002), Ritter et al. (2003), Hansen et al. (2007) and Rosenqvist et al. (2010).

The soil is a sandy loam up to 120 cm depth, developed from calcareous till deposit which appear to be relatively homogeneous over the area (Table 2). It is classified as a Stagnic Luvisol (IUSS Working Group WRB, 2006). There was lack of evidence of prolonged soil saturation due to a shallow watertable, but evidence of pseudogley below 45 cm indicated a periodically high watertable. The topography in the area is flat, causing surface runoff to be insignificant. On these fertile soils real organic layers were not formed and only recent litter and more coarse material were found on top of the mineral soil, except for the oldest spruce stand (VS69) that had a shallow (c. 2 cm) organic layer (Vesterdal et al., 2002). The climate in the study area is classified according to the Köppen–Geiger system as temperate fully humid with warm summer seasons, corresponding to Cfb (Kottek et al., 2006). The site has a mean annual air temperature of 7.7 °C and mean annual precipitation of 625 mm for the period 1960–1990.

Table 1
Vegetation characteristics at Vestskoven.

Tree species	Abbreviation	Mean tree height[a] (m)	Stem density[a] (Stems ha^{-1})	Basal area[a] (m^2 ha^{-1})	*LAI*[b] (–)	$S_{c,C}$[b] (mm)
Oak						
	VO93	2.6	4071	4.3	2.9	0.7
	VO79	11.0	2671	29.8	5.0	1.5
	VO70	13.8	1085	21.4	6.0	1.4
Norway spruce						
	VS97	1.9	2512	1.2	2.9	1.8
	VS88	8.4	1896	19.1	4.6	1.5
	VS69	17.8	775	35.2	7.8	3.0

[a] Measured 2002 (Rosenqvist et al., 2010).
[b] Leaf area index (*LAI*) and canopy storage capacity ($S_{c,C}$) values for Vestskoven as estimated by Rosenqvist et al. (2010).

Table 2
Soil properties of VO70 and VS69 at Vestskoven.

Horizon	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	C (%)	Bulk density (Mg m^{-3})
Vestskoven, common oak (VO70)						
Ap	0–22	14.9	15.0	70.0	1.86	1.55
Btg	22–65	23.9	15.2	60.9	–	1.44
BC	65–85	8.2	6.9	84.8	–	1.59
Ckg	85–100	16.7	12.3	71.0	–	1.43
2Ckg	100–120	20.5	15.5	64.0	–	1.49
Vestskoven, Norway spruce (VS69)[a]						
O	−3–0					
Ap	0–20	14.9	16.9	68.2	2.54	1.01
Bt	20–32	27.9	16.4	55.7	0.41	1.52
Bt(g)	32–48	27.0	15.3	57.7	0.32	1.29
Btg	48–85	22.9	16.2	60.9	0.18	1.48
Ckg	85–95	21.8	17.0	61.2	–	1.48
Ck(g)	95–120	19.7	16.3	64.0	–	1.22

[a] From Rosenqvist et al. (2010).

Data on daily sum of air temperature, precipitation, air humidity, wind speed and global radiation were obtained from the Danish Meteorological Institute (DMI) stations at Højbakkegård and Værløse during the study period, located 4 and 8 km, respectively, from Vestskoven.

In each forest stand, three circular subplots (20 m diameter) were established and used for all measurements. Soil water content was measured using TDR equipment (Prenart TDR system, Denmark). Stationary TDR probes were inserted vertically within fixed depth intervals of 0–0.2 m and 0–0.9 m. Measurements were carried out using a Tektronix cable tester and a handheld PC once a month between April 2001 and December 2002 at three TDR measurement points in each circular subplot, giving nine determinations per depth in each forest stand. The measurements continued only in the oldest oak stand (VO70) until March 2010.

Bulk precipitation and throughfall volume were measured monthly between January 2001 and December 2002. Five throughfall funnels were installed at 1 m height, four at the cardinal points and one in the centre of each circular subplot. In clearings within the forest, two funnels similar to those used for throughfall were installed for collection of bulk precipitation. More details on the equipment and methods used for measuring TDR, precipitation and throughfall can be found in Hansen et al. (2007) and Rosenqvist et al. (2010).

2.2. DAISY model description

The DAISY model has been developed for simulation of water and N dynamics and crop growth in agro-ecosystems. A detailed description of the model can be found in Hansen et al. (1990) and Abrahamsen and Hansen (2000). The water balance components of the model that relate to forest stands deal with the water balance of the surface and the soil, where the atmosphere and the groundwater constitute the boundaries of the system. The fluxes considered at the surface are precipitation (gain), and evapotranspiration and surface runoff (losses), whereas fluxes at the lower boundary of the system are deep percolation (loss) or capillary rise (gain). Soil water dynamics are modelled by a numerical solution to Richards's equation. In the present simulations, evapotranspiration was described using the potential evapotranspiration concept and the forest stands were simulated using the permanent vegetation DAISY module described by Boegh et al. (2009). In the DAISY model, potential evapotranspiration (E_p) is calculated as:

$$E_p = K_c ET0 \qquad (1)$$

where $ET0$ is the reference evapotranspiration and K_c is the reference evapotranspiration factor (crop coefficient). Boegh et al. (2009) used K_c to adjust for differences in climate and vegetation characteristics (leaf area index (*LAI*), height, roughness) between the reference grass canopy and the actual forest canopy. $ET0$ is calculated using the FAO Penman–Monteith combination equation (Allen et al., 1998).

The values of *LAI* vary over the year in broadleaved trees such as oak, with the maximum values observed in summer and the minimum values in winter and early spring (Bréda and Granier, 1996). In this study, the *LAI* variation over the year (*LAIvsDAY*) in oak trees was estimated by considering a simple *LAIvsDAY* distribution based on visual observations at the Vestskoven experimental site. It included as maximum *LAI* values, the *LAI* estimated and used by Rosenqvist et al. (2010). Fig. 1 shows *LAIvsDAY* in the oak stand planted in 1970 (VO70). In contrast, since conifer trees show low *LAI* seasonal variations over the year (Alavi et al., 2001), a constant *LAI* was assumed for spruce stands during the whole year, which was based on *LAI* values measured at the site by Rosenqvist et al.

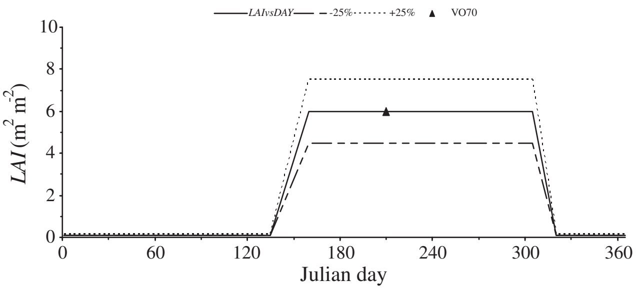

Fig. 1. Variation in LAI over the year (*LAIvsDAY*) in the oak stand planted at Vestskoven in 1970 (VO70) (solid line), dashed lines indicate ±25% *LAI* over the year factor (LAI_{factor}) limits. Triangle indicates estimated summer *LAI* value in VO70 (Table 1).

(2010). To estimate model sensibility to the *LAI* values within the oak and spruce stands, an arbitrary ±25% *LAI* over the year factor (LAI_{factor}) was applied (Fig. 1). This parameter was included in the GLUE procedure as described in detail later.

Part of the precipitation reaching the forest is intercepted by the tree canopy, which acts as interception storage. The direct throughfall is assumed to be a function of the *LAI* and is estimated as:

$$J_{w,d} = Pe^{(-K_I LAI)} \tag{2}$$

where $J_{w,d}$ is direct throughfall, P is precipitation and K_I is an empirical distribution coefficient. Water intercepted by the canopy may be evaporated, stored or flow to the ground as canopy throughfall or stemflow. The evaporation from the interception storage (E_I) is estimated as:

$$E_I = Min\left\{\frac{S^t_{w,C}}{\Delta t} + P - J_{w,d}; E_{p,C}\right\} \tag{3}$$

where $S_{w,C}$ is storage of intercepted water, $E_{p,C}$ is potential canopy evapotranspiration and Δt is the time step. The flow to the ground as throughfall ($J_{w,C}$) is estimated as:

$$J_{w,C} = Max\left\{\frac{S_{c,C}}{\Delta t} - \left(\frac{S^t_{w,C}}{\Delta t} + P - J_{w,d} - E_I\right); 0\right\} \tag{4}$$

where $S_{c,C}$ is canopy storage capacity, which is assumed to be proportional to *LAI*:

$$S_{c,C} = IntcpCap \; * \; LAI \tag{5}$$

where *IntcpCap* is canopy water interception capacity coefficient. Finally, the updated canopy storage is calculated as:

$$S^{t+\Delta t}_{w,C} = S^t_{w,C} + (P - J_{w,d} - J_{w,C} - E_I)\Delta t \tag{6}$$

2.3. Estimation of soil hydraulic properties

Soil hydraulic properties were derived using Campbell's hydraulic conductivity model (Campbell, 1974), which is given by:

$$K = K_s(\frac{\theta}{\theta_s})^{Ab+B} \tag{7}$$

where K is unsaturated hydraulic conductivity, K_s is saturated hydraulic conductivity, θ is the water content of the soil, θ_s is the saturated water content and b is the Campbell water-retention parameter; with $A = 2$ and $B = 3$ derived from pore size distribution and adding a pore-connectivity term according to Campbell (1974) in combination with Burdine theory. The Campbell soil water retention model is expressed as:

$$\theta = \theta_s\left(\frac{h_b}{h_p}\right)^{\frac{1}{b}} \tag{8}$$

where θ_S is saturated water content, h_b is soil water pressure head and h_p is air entry potential. In this study, the inverse procedure was used to estimate the parameters b and h_b in Eq. (8) by assuming values for water content at field capacity (θ_{FC}) and water content at wilting point (θ_{WP}). According to Madsen and Platou (1983), θ_{FC} and θ_{WP} correspond to the water content at pF 2.0 and pF 4.2, respectively.

2.4. Model calibration and uncertainty estimation

The DAISY inputs used in this study were based on field measurements at Vestskoven reported by Vesterdal et al. (2002), Ritter et al. (2003) and Rosenqvist et al. (2010). The GLUE procedure was used to calibrate and quantify the uncertainty in soil water content over 0–90 cm. GLUE estimates were compared with monthly soil water content measurements performed within each stand during the monitoring period, between April 2001 and December 2002 (19-month calibration period). The GLUE methodology was applied separately to the three oak stands (VO93, VO79 and VO70) and the three Norway spruce stands (VS97, VS88 and VS69). Data for the period January 2003–March 2010 (75 months) were only available for the VO70 stand, so these data were used to evaluate the model performance in predicting medium-term soil water content over 0–90 cm. The median of the nine observed monthly soil water contents at 0–90 cm was calculated for comparison with GLUE estimates obtained for the study period.

The general requirements of the GLUE procedure can be summarised as follows: (i) a formal definition of a likelihood measure; (ii) an appropriate definition of the prior parameter distribution; and (iii) a procedure for using likelihood weights in uncertainty estimation. In some of these steps a number of subjective decisions must be made, such as in choice of likelihood measure, prior parameter range and threshold of acceptability.

2.4.1. Definition of a likelihood measure

The traditional statistical likelihood measure modelling efficiency (E) was tested as likelihood function (Nash and Sutcliffe, 1970) for soil water content simulations:

$$E = 1.0 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O')^2} \tag{9}$$

where O_i is the individual observed soil water content value at time i, S_i is the individual simulated soil water content value at time i, O' is the mean observed soil water content value and n is the number of paired observed-simulated values. The value of E ranges from minus infinity to 1.0, where an E value of 1.0 represents a perfect prediction and lower values indicate less accurate agreement between the model and observations (Nash and Sutcliffe, 1970). Thus a value of zero for E indicates that O' is as good a predictor as the model, whereas negative values indicate that the observed mean is a better predictor than the model.

Beven (2008) indicated that the likelihood threshold for a model to be considered behavioural is site-specific and should consider the main objectives of each modelling project. In this study, only simulations with $E \geqslant 0.5$ were retained for making predictions and were classified as behavioural simulations. It was assumed that this value reflects a minimum acceptable model performance, given the current observed data available. Parameter sets with E values lower than the likelihood threshold were classified as non-behavioural simulations and given a likelihood of zero.

2.4.2. Definition of a priori parameter distribution

When it is not possible to optimise all the parameters required in a modelling approach, most emphasis in the GLUE methodology must be placed on sensitive parameters that are important to give a good fit to the observed values (Beven, 2006). In this study, parameters that had sporadic measurements, such as *LAI*, and parameters that were not measured at Vestskoven were calibrated using the GLUE methodology. In all, eight parameters were included in the GLUE procedure. Four of these eight parameters were related to water losses, viz. evaporation from interception storage, soil evaporation and transpiration. These parameters were: *LAI* over the year factor (LAI_{factor}); canopy water interception capacity coefficient (*IntcpCap*); potential evapotranspiration factor (K_c); and maximum rooting depth (*MaxPen*).

The distribution of parameter values for LAI_{factor}, *IntcpCap* and K_c was initially defined on the basis of values from the literature. Later, these parameters were adjusted by comparing DAISY simulation results with measured monthly throughfall during summer, whereas *MaxPen* was estimated from literature values alone. Parameter ranges for oak and Norway spruce stands are shown in Tables 3 and 4, respectively.

The other four parameters corresponded to soil hydraulic parameters included in the Campbell model, such as: hydraulic conductivity at field capacity (K_{FC}); water content at wilting point (θ_{WP}); saturated water content at field capacity (θ_{FC}); and saturated water content (θ_s). It was assumed that water content at 0–20 cm depends mainly on hydraulic soil properties in the Ap soil horizon, whereas water content at 0–90 cm depends mainly on hydraulic soil properties in the Btg soil horizon, which is the thickest horizon. Therefore, the four Campbell model parameters for the Ap soil horizon were pre-calibrated in each stand by comparing monthly observed and simulated water content values over 0–20 cm between April 2001 and December 2002, whereas for the Btg soil horizon, the water content over 0–90 cm was included in the GLUE procedure. Thus, in the Btg soil horizon, θ_{FC}, θ_{WP} and θ_S range values were based on comprehensive soil physical studies in coarse-textured soils in Denmark carried out by Madsen and Platou (1983) and Hansen et al. (1986). In addition, it was assumed that K_{FC} (pF 2) ranged between 10^{-7} m s^{-1} and 10^{-6} m s^{-1}. Table 5 shows the calibrated values for the Campbell model for the Ap soil horizon and the parameter ranges used in the GLUE analysis in the Btg soil horizon at the Vestskoven site.

For the calibration period (April 2001–December 2002), 10,000 Monte Carlo sets of parameters were generated from uniform distributions across the specified ranges shown in Table 3 for oak stands, Table 4 for Norway spruce stands and Table 5 for parameter values for the Campbell model in Btg soil horizons.

2.4.3. Procedure for using likelihood weights in uncertainty estimation

The *E* values were scaled in such a way that the sum of all *E* values was equal to 1, resulting in a distribution function for the parameter sets. To calculate a cumulative distribution of the predictions, the soil water contents predicted by each sample model run during the simulation period were ranked in order of magnitude, using the likelihood weights associated with each simulation. For the present study, the 5% and 95% percentiles of the cumulative likelihood distribution were chosen as the uncertainty limits of the predictions.

2.5. Sensitivity analysis

A sensitivity analysis was carried out for all parameters selected in the Monte Carlo simulations (Table 2–4) using the GLUE results. This methodology considers the likelihood weights for the

Table 3
Parameter ranges for oak stands used in Monte Carlo simulations for the DAISY model.

Parameter	Unit	Description	Minimum value	Maximum value	Sources
LAI_{factor}	–	Leaf area index over the year factor	0.75	1.25	Assumed in this study
IntcpCap	mm	Canopy water interception capacity coefficient	0.05	0.15	Rosenqvist et al. (2010)
K_c	–	Potential evapotranspiration factor	0.4	1.0	Allen et al. (1998), Verstraeten et al. (2005), Boegh et al. (2009)
MaxPen	cm	Maximum penetration rooting depth	100	200	Rosengren and Stjernquist (2004)

Table 4
Parameter ranges for Norway spruce stands used in Monte Carlo simulations for the DAISY model.

Parameter	Unit	Description	Minimum value	Maximum value	Sources
LAI_{factor}	–	Leaf area index over the year factor	0.75	1.25	Assumed in this study
IntcpCap	mm	Canopy water interception capacity coefficient	0.25	0.45	Rosenqvist et al. (2010)
K_c	–	Potential evapotranspiration factor	0.7	1.1	Allen et al. (1998) and Boegh et al. (2009)
MaxPen	cm	Maximum rooting penetration depth	50	150	Rosengren and Stjernquist (2004)

Table 5
Calibrated parameter values for the Campbell model in the Ap soil horizon and parameter ranges in the GLUE analysis for the Campbell model in the Btg soil horizon in the stands Vestskoven common oak (VO70, VO79 and VO93) and Norway spruce (VS69, VS88 and VS97).

Soil horizon	Parameter[a]	Forest stand					
		VO70	VO79	VO93	VS69	VS88	VS97
Ap	K_{FC} (m s^{-1})	6×10^{-7}	5×10^{-7}	6×10^{-7}	6×10^{-7}	5×10^{-7}	4×10^{-7}
	θ_{WP} (cm^3 cm^{-3})	0.12	0.11	0.12	0.09	0.09	0.12
	θ_{FC} (cm^3 cm^{-3})	0.27	0.26	0.28	0.24	0.22	0.26
	θ_s (cm^3 cm^{-3})	0.42	0.40	0.41	0.41	0.35	0.40
Btg	K_{FC} (m s^{-1})	10^{-7}–10^{-6}	10^{-7}–10^{-6}	10^{-7}–10^{-6}	10^{-7}–10^{-6}	10^{-7}–10^{-6}	10^{-7}–10^{-6}
	θ_{WP} (cm^3 cm^{-3})	0.10–0.18	0.10–0.18	18–24	14–22	14–22	14–22
	θ_{FC} (cm^3 cm^{-3})	0.27–0.35	0.27–0.35	40–48	27–35	27–35	27–35
	θ_s (cm^3 cm^{-3})	0.37–0.45	0.37–0.45	49–57	37–45	37–45	37–45

[a] K_{FC} is the hydraulic conductivity at field capacity, θ_{WP} is the water content at wilting point, θ_{FC} is the saturated water content at field capacity and θ_s is the saturated water content.

behavioural simulations (Beven, 2008). The sensitivity analysis was performed by comparison of the cumulative distribution for the posterior behavioural simulations of soil water content (0–90 cm) simulations and non-behavioural simulations. The parameters that showed a strong deviation between behavioural and non-behavioural cumulative distributions across the same parameter range were considered the most sensitive. In contrast, parameters that were uniformly distributed were considered less sensitive to changes in parameter values.

2.6. Long-term virtual stand simulations

To evaluate the effects of forest dynamics (i.e. growth and canopy expansion) on the water balance in the long-term, 35-year simulations were performed using calibrated parameters in the GLUE procedure for oak (Table 3) and Norway spruce (Table 4). Parameters, such as height, *LAI* over the year (*LAIvsDAY*) maximum values, canopy water interception capacity coefficient (*IntcpCap*), potential evapotranspiration factor (*Kc*) and maximum rooting depth (*MaxPen*), were linearly transformed in small steps year-by-year. The climate record available for the zone (1998–2010) was repeated, starting each of the measured stands at the time when these fitted the timeline. In the simulations the same type of soil (VO70, see Table 2) was used to compare both tree species under the same conditions.

3. Results and discussion

3.1. Model calibration and uncertainty estimation

The results of GLUE analysis depend on the choice of likelihood measure used to evaluate the sample of models and the choice of limits of acceptability (Beven, 2008). All water content values simulated for the 0–90 cm soil layer with modelling efficiency (*E*) values greater than or equal to 0.5 were accepted as behavioural. Although in some stands less than 5% of the simulations were classified as behavioural (Table 6), these were enough to allow a number of observed data to be compared with the GLUE estimates (5% and 95%). The predicted 5% and 95% uncertainty limits defined during the calibration period (April 2001–December 2002) are shown in Figs. 2 and 3 for the oak and Norway spruce stands, respectively.

The temporal trend and magnitude of observed monthly soil water content over 0–90 cm were well predicted by the model during the calibration period, when the uncertainty bands included more than 68% of the monthly observed values in the forest stands, except for Norway spruce stand VS88, which only included 50% (see Figs. 2 and 3). In VO70, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 4% smaller and 6% higher for the calibration period and 12% and 18% higher for the validation period. In VO79, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 4% smaller and 6% higher for the calibration period. In VO93, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 1% smaller and 3% higher for the calibration period. On the other hand in VS69, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 1% and 4% higher for the calibration period and 9% and 11% lower for the validation period. In VS88, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 5% smaller and 7% higher for the calibration period. In VS97, compared with mean observed soil water content at 0–90 cm values, the mean GLUE estimates (5% and 95%) were 4% smaller and 9% higher for the calibration period. Although, a lower agreement in VO93, VS69 and VS88 was found between the GLUE estimates and some median of observed soil water content at 0–90 cm, those had a much less weight on the overall performance of the DAISY model during the calibration period and are related with possible sources of uncertainty that are explained later. In addition, the maximum *E* values obtained in the behavioural simulations ranged from 0.56 to 0.78 (Table 6), which indicated good agreement between observed and simulated water content at 0–90 cm. In all forest stands in periods when the soil water content at 0–90 cm was high, e.g. in winter and early spring, the width of the bands for the calibration period was also high, which indicated that the uncertainty in this prediction was high.

Table 6
Results of the GLUE analysis.

Tree species	Abbreviation	Number of behavioural simulations ($E \geqslant 0.5$)[a]	Maximum E value[a]
Oak	VO93	196	0.65
	VO79	469	0.67
	VO70	77	0.56
Spruce	VS97	4567	0.71
	VS88	1278	0.78
	VS69	27	0.53

[a] E is the modelling efficiency.

The results suggest that the parameters controlling water movement under saturated conditions, such as soil hydraulic properties, are associated with considerable uncertainty. Other field studies carried out in Denmark (Djurhuus et al., 1999; Ladekarl et al., 2005) have shown that the spatial variability in soil hydraulic properties and the presence of preferential flow directly affect the spatial variation in soil water content, even in small areas. In this regard, Coners and Leuschner (2005) found that soil hydraulic properties show significant spatial variability in many forest soils, which would further increase the patchiness of water uptake. Ladekarl (1998) pointed out that the influence of stem distance on soil water content, canopy drip points and root water uptake may contribute to the high number of replicates needed to characterise the trend and magnitude of soil water content in a forest soil. She also pointed out that the process of root water uptake is poorly understood and has important consequences for hydrological modelling in forest soils.

When the water content measurements at 0–90 cm for the period January 2003–March 2010 were compared with GLUE estimates (5% and 95%) obtained during the calibration period for the VO70 forest stand, good agreement was observed (Fig. 2). The uncertainty prediction bands mostly followed the general trend of the observed soil water content over 0–90 cm, but in some cases the observed soil water content over 0–90 cm crossed over the bounds of the prediction bands.

3.2. Sensitivity analysis

The sensitivity of the DAISY model performance to the most important parameters was explored using a form of global sensitivity analysis for the behavioural simulations. The results are shown for VO79 and VS88, which represent the general tendencies in oak and Norway spruce stands, respectively (Fig. 4). Comparing results from the sensitivity plots in oak and Norway spruce stands, the reference evapotranspiration factor (K_c) and the soil hydraulic parameters included in the Campbell model, such θ_{WP}, θ_{FC} and θ_s, showed a strong deviation between behavioural ($E \geqslant 0.5$) and non-behavioural ($E < 0.5$) cumulative distributions. The high sensitivity to the parameter K_c in all treatments reflects the role of evapotranspiration as a process of direct loss of water from the soil–plant system, which has a considerable impact on the water balance in a forest

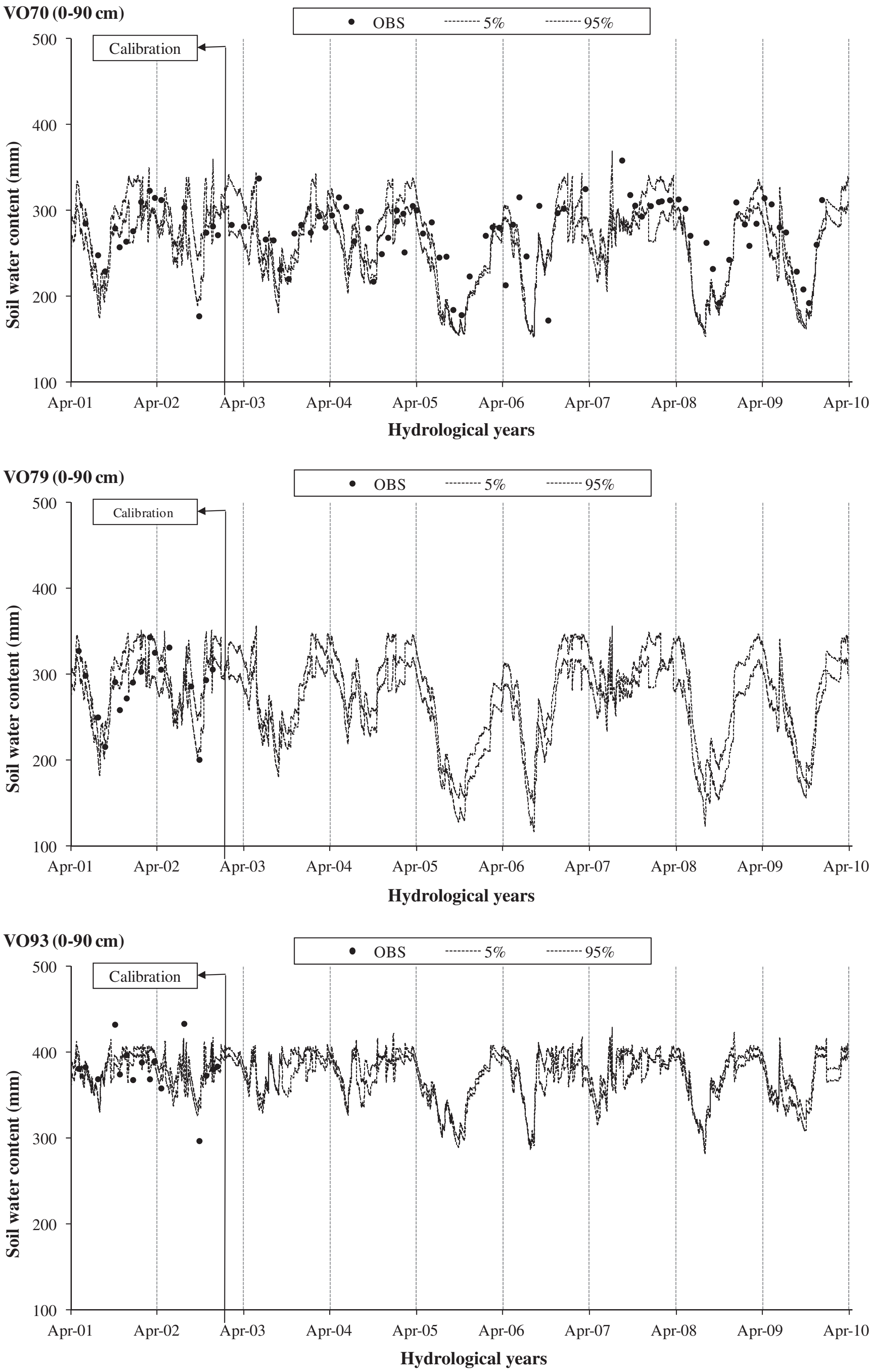

Fig. 2. Predictive uncertainty of results for the calibration period April 2001–December 2002 and the study period April 2001–March 2010 in oak stands. Symbol (●) indicates the median of observed soil water content at 0–90 cm in each stand. Black dashed lines indicate 5% and 95% simulation limits and grey lines indicate different hydrological years.

stand. Similarly, Boegh et al. (2009) pointed out the importance of accurate evapotranspiration parametisation at all spatial scales for assessing groundwater recharge. Furthermore, soil hydraulic properties have been identified as a sensitive parameter in hydrological modelling in forest soils because these parameters directly affect the water movement in the soil. For instance, Verstraeten et al.

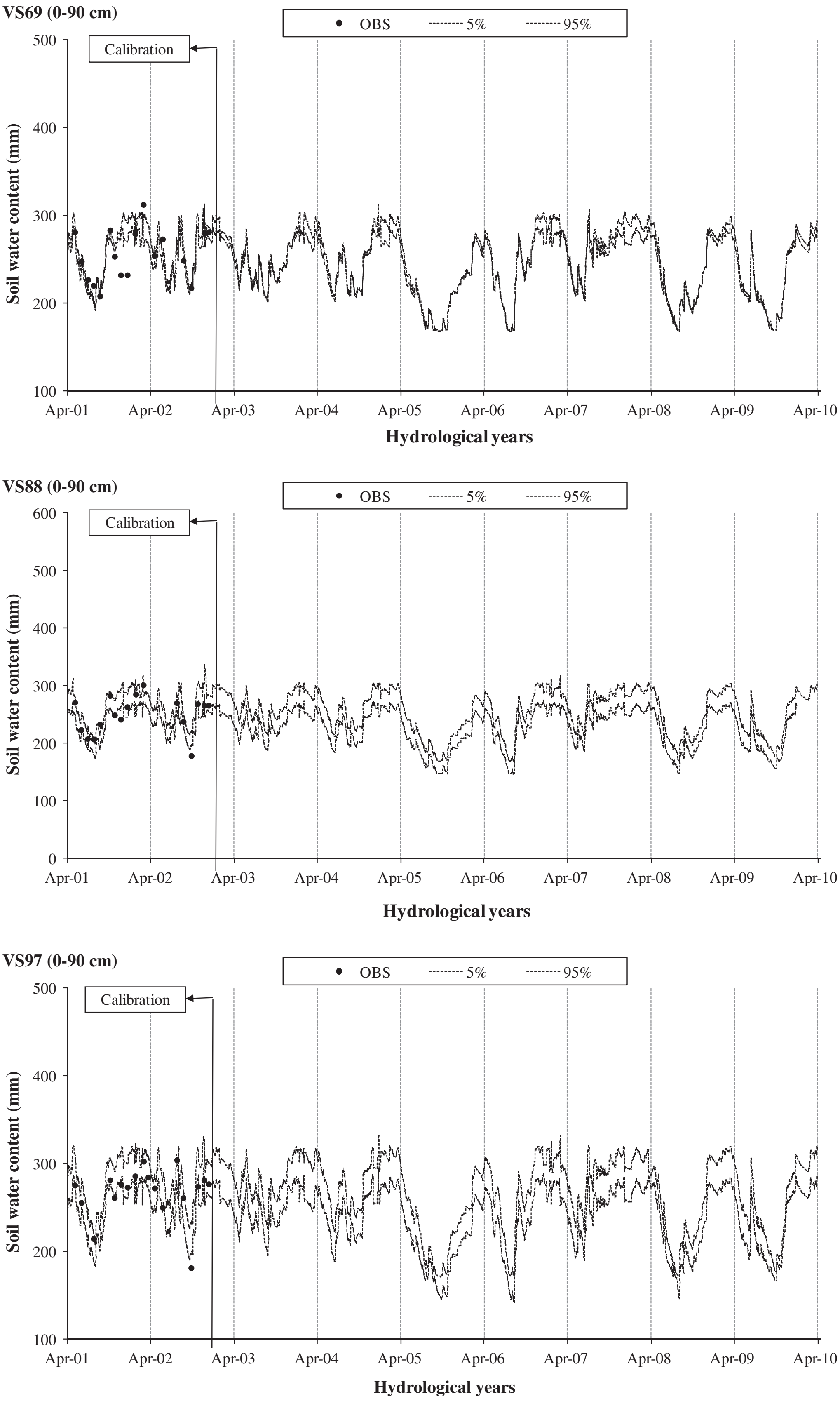

Fig. 3. Predictive uncertainty of results for the calibration period April 2001–December 2002 and the study period April 2001–March 2010 in Norway spruce stands. Symbol (•) indicates the median of observed soil water content at 0–90 cm in each stand. Black dashed lines indicate 5% and 95% simulation limits and grey lines indicate different hydrological years.

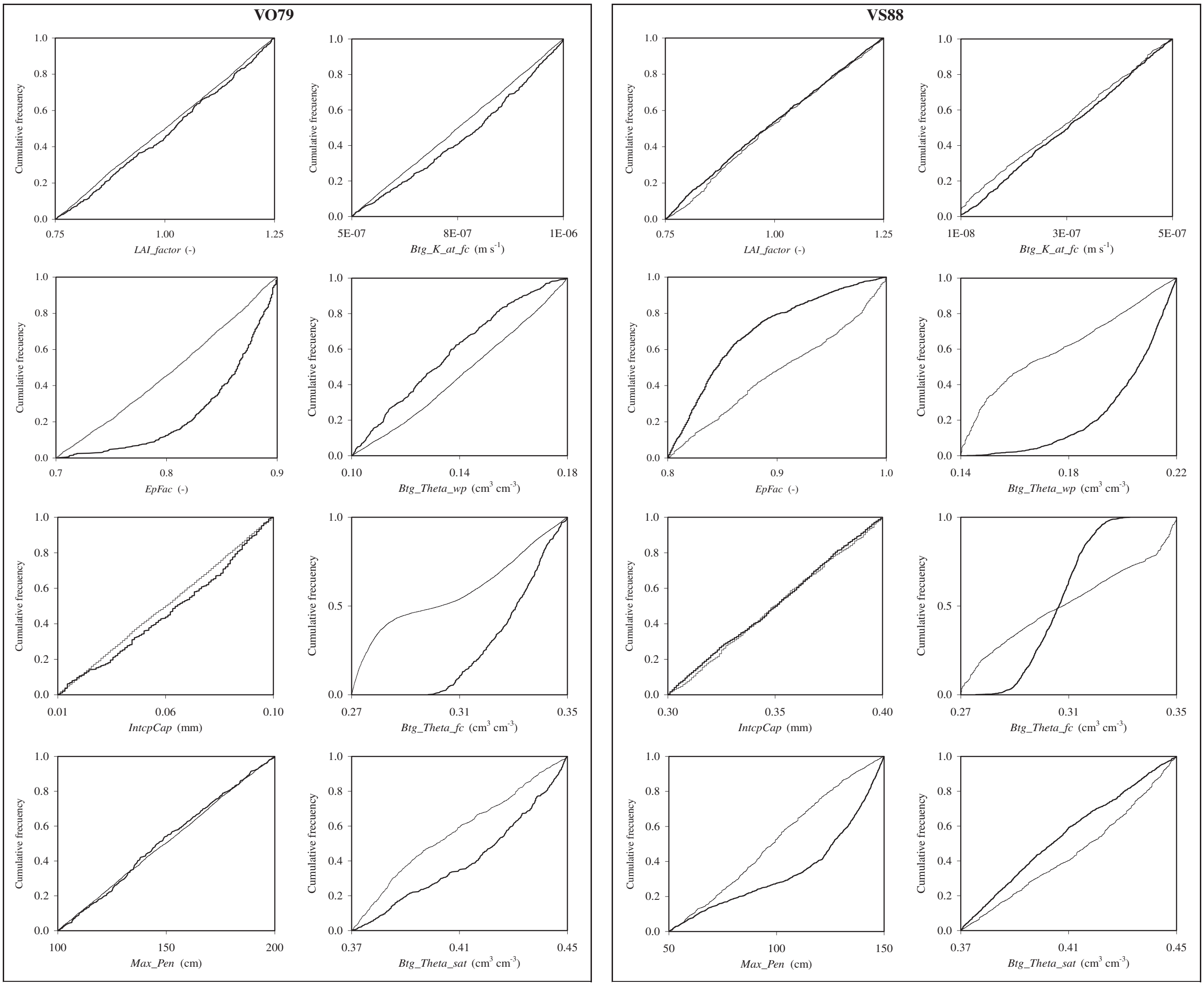

Fig. 4. Sensitivity plots for all parameters included in the GLUE procedure (see Tables 3–5) for water content at 0–90 cm predictions in forest stands VO79 and VS88. Solid lines indicate behavioural parameter distributions ($E \geqslant 0.5$) and dashed lines indicate non-behavioural parameter distributions ($E < 0.5$).

(2005), using the WAVE model, found that the K_c and hydraulic soil properties were sensitive parameters in soil water content simulations in forest stands.

The rising limbs of the cumulative distributions associated with the parameter maximum penetration rooting depth (*MaxPen*) imply that it is rather sensitive in the Norway spruce stands. This may indicate that better characterisation of water uptake in tree root systems is necessary in the model, since it is well documented that there is high spatial variability in root activity in a forest soil, even if soil texture and moisture are more or less homogeneous (Coners and Leuschner, 2005).

Other parameters, such as *LAI* over the year factor (LAI_{factor}), canopy water interception capacity coefficient (*IntcpCap*) and hydraulic conductivity at field capacity (K_{FC}), proved to be insensitive because of the similarity between their respective cumulative distributions across the whole extent of the parameter ranges inspected.

This type of visual sensitivity analysis on the basis of the shape of cumulative distributions can be used to refine the search ranges for additional Monte Carlo simulations in future model applications (Vázquez et al., 2009). Thus, for highly sensitive parameters, the sampling should be targeted at the range within which most of the behavioural simulations are concentrated.

3.3. Water balance in the forest stands

The DAISY simulation results revealed important differences between oak and Norway spruce stands (Table 7). During the period April 2001–March 2010, simulated mean annual outputs showed that in the spruce stands 16–25% of the incoming precipitation led to water recharge (percolation), whereas water recharge in the oak stands ranged between 25% and 47% of incoming precipitation. Rosenqvist et al. (2010) evaluated the SWAP model in the same field experiment using the hydrological year April 2001–March 2002 and reported similar results. Similar tendencies have also been reported by van der Salm et al. (2007) using data from oak and Norway spruce stands in the Netherlands, Sweden and Denmark. They concluded that in spruce stands, 5–30% of incoming precipitation leads to water recharge to groundwater and surface water, whereas in the oak stands 20–35% of incoming precipitation becomes water recharge. All studies attribute this lower water recharge in Norway spruce to higher interception evaporation losses in spruce stands than in oak stands.

A decline in water recharge was evident in oak and Norway spruce chronosequences during the 40 years after afforestation, which was mainly caused by an increase in interception evaporation losses with increasing forest age. van der Salm et al. (2006)

Table 7
Simulated mean annual actual evapotranspiration and water recharge in oak and Norway spruce during 9 hydrological years (April 2001–March 2010) using constant stand parameters (i.e. stand development not included). Range of data indicate 5% and 95% simulation limits.

Tree species	Abbreviation	Actual Evapotranspiration (mm year^{-1})	% of *PP*[a]	Water recharge (mm year^{-1})	% of *PP*[a]
Oak					
	VO93	349–379	51–55	292–323	43–47
	VO79	503–505	73–74	170–171	25
	VO70	501–507	73–74	169–172	25
Norway spruce					
	VS97	508–518	74–76	164–171	24–25
	VS88	538–549	78–80	138–147	20–21
	VS69	565–581	82–85	112–125	16–18

[a] Outputs are also given as percentage of precipitation (*PP*). Mean annual *PP* between April 2001 and March 2010 was 686 mm.

noted that under comparable conditions, the increase in interception losses with age should be faster in coniferous forest than in deciduous forest. Similarly, in the present study the lowest water recharge (representing 16–18% of mean annual precipitation) was found in the oldest Norway spruce stand (VS69). In another study in Denmark, Christiansen et al. (2006) used CoupModel and reported that only 5% of incoming precipitation led to water recharge in a 40-year-old Norway spruce stand. This was lower than the proportion in a 23-year-old deciduous beech (*Fagus sylvatica* L.) stand, where 34% of mean annual precipitation became recharge.

The oldest oak stand in this study (VO70) lost between 72% and 74% of incoming precipitation as evapotranspiration and 25% of incoming precipitation as water recharge. A study in a 150-year-old Danish oak stand by Ladekarl (1998) found that mean annual evapotranspiration removed 50% of precipitation, while water recharge ranged from 47% to 52%. However, this forest stand was located in a coarser-textured soil (95% sand at 0–90 cm depth) compared with the Vestskoven field experiment (56–68% sand at 0–90 cm depth). The higher water recharge may be related to higher water percolation in the coarser-textured soil.

3.4. Long-term virtual stand simulations

The 35-year simulations of changes in virtual oak and Norway spruce stands on the same soil and using the same climate data clearly showed a decline in water recharge after the 10-year point, when usually less than 200 mm year^{-1} of water recharge (WR) and more than 400 mm year^{-1} of actual evapotranspiration (ETa) were predicted for both tree species (Fig. 5). Norway spruce displayed a higher reduction in water recharge than oak, with a water recharge average after the 30-year point of 58 mm year^{-1} for Norway spruce and 142 mm year^{-1} for oak. A similar trend was observed in average ETa after the 30-year point, when Norway spruce had higher ETa values than oak (588 and 486 mm year^{-1}, respectively).

The precipitation (PP) varied widely between years, from 458 mm year^{-1} to 902 mm year^{-1}. In Norway spruce, when ETa > PP, particularly after the 12-year point and when the precipitation was lower than the mean annual precipitation of 625 mm, the water recharge reached the lowest values, around 25 mm year^{-1}. After the 30-year point, during a rainy year (902 mm year^{-1}), the difference in annual water recharge between oak and spruce was 174 mm year^{-1}, whereas in a dry year (PP = 458 mm year^{-1}), the

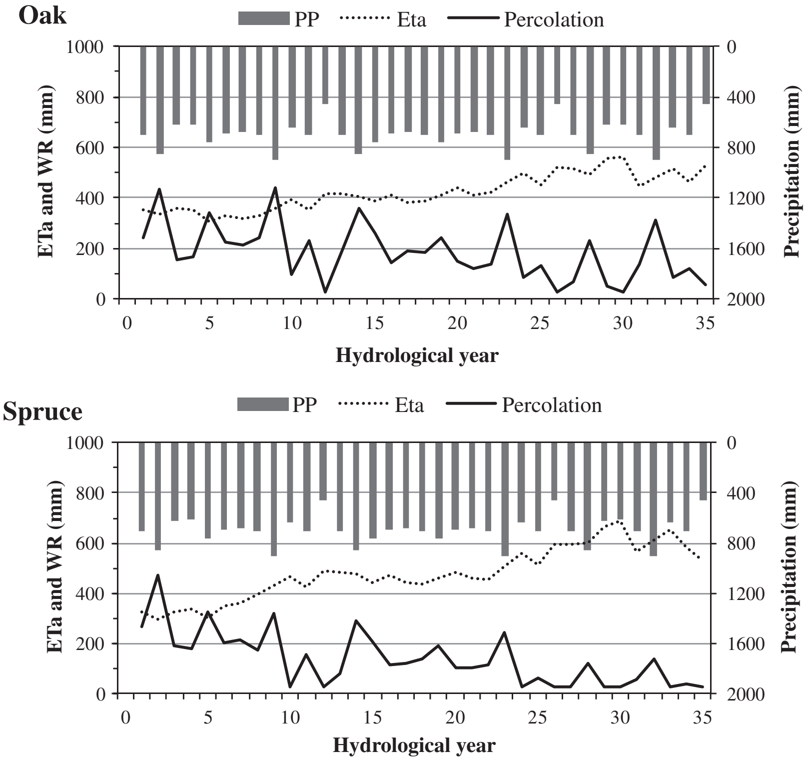

Fig. 5. Long-term virtual oak and Norway spruce simulations (35 years), including precipitation (PP), actual evapotranspiration (ETa) and water recharge (WR).

difference in annual water recharge between oak and spruce was 31 mm year^{-1}.

In consequence, the differences found on water recharge between oak and Norway spruce should be considered in afforestation projects in Denmark, because the majority of water used for domestic water supplies come from groundwater, where in some areas nearby field wells would be recommended to plant oak instead of Norway spruce to secure water availability in the future.

4. Conclusions

The agro-ecosystem model DAISY (Version 4.93) was evaluated using hydrological data from afforestation chronosequences of oak and Norway spruce in Denmark for nine hydrological years (April 2001–March 2010). The model was calibrated to simulate monthly soil water content over 0–90 cm in stands using data for the period March 2001–December 2002, and correctly predicted the temporal trend and magnitude of observed soil water content. In the oldest oak stand (VO70), the GLUE estimates obtained during the calibration period (uncertainty bands 5% and 95%) agreed satisfactorily with measured monthly soil water content over 0–90 cm in the period January 2003–March 2010.

Major discrepancies in predicting monthly soil water content over 0–90 cm were attributed to highly variable soil water content, which is directly related to the spatial variability in soil hydraulic properties that occur in a forest stand. However, Campbell's hydraulic conductivity model may be used as input to the DAISY model to simulate the water balance pattern with reasonable accuracy if an adequate number of soil water measurements are available to characterise the soil water trends.

The results showed that the composition of the vegetation cover is a key factor in the design of future afforestation projects. The predicted values indicated that water recharge is lower under Norway spruce than oak, owing to higher interception evaporation losses in spruce. The tree species present directly affects the water balance, particularly water recharge of groundwater reservoirs and especially as the stand matures. DAISY long-term simulations indicated that the general difference in annual water recharge between oak and Norway spruce was 31–174 mm year^{-1}, with higher differences during rainy years (precipitation >900 mm year^{-1}).

Overall, the agro-based DAISY model proved capable of evaluating the hydrological effects of afforestation and the model has potential for simulating future hydrological processes in afforestation projects.

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