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

Osvaldo Salazar [a,b,*], Søren Hansen [a], Per Abrahamsen [a], Karin Hansen [c,d], Per Gundersen [c]

[a] *Department of Plant and Environmental Sciences, Faculty of Science, University of Copenhagen, Thorvaldsensvej 40, DK-1871 Frederikberg C, Denmark*
[b] *Departamento de Ingeniería y Suelos, Facultad de Ciencias Agronómicas, Universidad de Chile, Casilla 1004, Santiago, Chile*
[c] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark*
[d] *IVL Swedish Environmental Research Institute, Box 210 60, S-100 31 Stockholm, Sweden*

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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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* Corresponding author at: Departamento de Ingeniería y Suelos, Facultad de Ciencias Agronómicas, Universidad de Chile, Casilla 1004, Santiago, Chile. Tel.: +56 2 2978 5834.
E-mail address: osalazar@uchile.cl (O. Salazar).

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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 1×3 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.