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Hydrology and Earth System Sciences Discussions

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The potential of observed soil moisture dynamics for predicting summer evapotranspiration in a successional chronosequence

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Abstract

The hydrology of ecosystem succession gives rise to new challenges for the analysis and modeling of water balance components. Recent large-scale alterations of forest cover across the globe suggest that a significant portion of new biophysical environments will influence the long-term dynamics and limits of water fluxes compared to pre-succession conditions. This study explores the potential of modeling actual evapotranspiration (AET) in the summer along a successional forest by observed soil moisture dynamics. We applied two parsimonious data-driven soil water balance models to the Canadian FLUXNET sites at Campbell River, British Columbia. Simulated AET was compared to water vapor measurements from 2001 to 2008 and the models' sensitivity to inter-annual climatic variability and computation time step was tested. With the exception of the mature forest during an extremely dry summer, the results confirm the potential of using observed soil moisture dynamics as a method to estimate summer AET within an acceptable error range albeit substantial differences along the successional forested ecosystem. The study suggests that summer AET could be estimated and monitored in many more places than those equipped with eddy-covariance or sap-flow measurements to advance the understanding of the water balance of different successional ecosystems.

1 Introduction

In particular forested ecosystems are strongly subjected to human disturbances (Bonan, 2008; Hansen et al., 2010) and natural environmental changes (e.g., Kurz et al., 2008). From the year 2000 to the year 2005, more than 1 million km^2 of global forest cover was either converted to agricultural land or altered into developing successional forests (Hansen et al., 2010). Due to the magnitude of recent large-scale disturbances, the long-term effects of ecological succession on the exchanges between the atmosphere and a recovering biosphere are a major concern. In temperate and boreal land-

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scapes, previous studies have found substantial differences in the carbon cycle (Sitch et al., 2003; Magnani et al. 2007; McMillan et al., 2008) and energy budget (Amiro et al., 2006; Juang et al., 2007) of differently aged forest including post-disturbance forest succession. Forest hydrology studies have long focused on post-disturbance flood increase, but few studies have attempted a quantification of the systematic influence of a recovering forest on the water balance. Jassal et al. (2009) found that in a Douglas fir succession initially reduced evapotranspiration (AET) recovered 12 years after disturbance. Brena Naranjo et al. (2011) detected a recovery effect on AET in forest chronosequences and on the water balance in various watersheds in the North American West. Although changes in AET exhibited a different timing, a gradual recovery was common for at least 60 years after disturbance. The uncertainty in estimating the timing of such long-time recovery leaves open questions about the complexity to predict annual or seasonal AET in a post-disturbance forest cover scenario.

Micrometeorological data from experimental forested sites that allow to examine the effects of disturbance and succession on water, energy and biogeochemical fluxes is limited to a few research sites along chronosequences (e.g., Stoy et al., 2006; Jassal et al., 2009). However the scale of disturbance calls for more research and in particular for better monitoring of the water balance. In transitional climate zones such as those with a Temperate to Mediterranean Climate Type this concerns particularly the summer AET of changing ecosystems. The aim of this study is to explore the potential of using observed soil moisture dynamics for the prediction of AET during the summer season along a successional forest chronosequence in such a climate. The use of soil water depletion to estimate AET for specific dry periods during summer has been recently studied by Schwärzel et al. (2009) and Schelde et al., (2010). The present work extends their approach over a longer time period and across a forest succession. It is guided by the following questions: (1) can a parsimonious data-driven model based on soil moisture observations be used for predicting summer AET in forested ecosystems and (2) is the prediction with this model sensitive to forest age, interannual climatic variability, and computational or observational time step?

2 Study site

This study used data from an evergreen forest chronosequence located on the east coast of Vancouver Island, BC, Canada. The Campbell River FLUXNET research site (Baldocchi et al., 2001) consists of three differently aged coastal Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands: a young (YS), intermediate (IS) and mature stand (MS). Published data available to the scientific community was obtained online (http://www.fluxnet-canada.ca/). The climate at the sites is characterized by cool and rainy winters and, dry and relatively warm summers. Mean annual precipitation is 1497 mm and the mean annual temperature is 9 °C. The average growing season extends from March to October. From May to October the region has climatic moisture deficits with the largest values in July and August (Moore et al., 2010). Soil texture at all sites is in the range from gravely loamy sand to sand. Humphreys et al. (2006) and Jassal et al. (2009) described further details about the sites (Table 1).

A meteorological tower sampled the vertical exchanges of latent heat above each stand using the eddy covariance technique. Half-hourly fluxes of water vapor were provided from three-axis anemometers and infrared gas analyzers, and volumetric soil water content were available from two locations at each site equipped with time-domain reflectometry (TDR) sensors reporting depth ranges of 0–30, 0–60 and 0–100 cm with a time resolution of 30 min (Jassal et al., 2009). The mean annual energy balance closure at the YS, IS and MS was 0.89, 0.83 and 0.88, respectively (Jassal et al., 2009). The study period covered seven summer seasons at the young and mature stands from June 2001 to September 2008. Observations at the intermediate stand began in 2002.

3 Modeling approach and evaluation

During summer dry periods the soil water balance is proportional to the root water uptake and to evaporation from the soil. Previous research suggested that soil moisture

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limits evapotranspiration, especially during water stress periods (Teuling et al., 2006a, b). In this study we consider the soil moisture dynamics in a soil layer from 0 to 30 cm during a summer period of 100 days from the end of June to the beginning of October (DOY 175 to 275). Two parsimonious data-driven soil water balance models with different complexity were tested across the three differently aged stands. Furthermore, two different model time steps, half-hourly and daily were used.

The models do not consider physical and biological drivers of evapotranspiration such as net radiation, vapor pressure deficit, leaf area index and canopy conductance, but assume that the soil water balance can be described as:

$$Z_{\mathrm{r}}\frac{d\theta(t)}{dt}=P(t)-q(t)-\mathrm{AET}(t) \tag{1}$$

where Z_{r} is the active root depth, P is rainfall, q is percolation, AET is evapotranspiration and θ is the volumetric soil water content. For further simplification, we assume that the value of Z_{r} and the soil depth where soil moisture limits evapotranspiration is similar.

This simple water balance model (Model I) may be valid in young stands where rainfall interception is low. Nevertheless, as forests transition to mature ecosystems, interception will play an important role in evapotranspiration (e.g. Savenije, 2004). A second water balance model (Model II, Eq. 2) therefore added an interception threshold value of 0.5 mm/h (Gash, 1979). The water vapor exchange from the canopy to the atmosphere is assumed to be 0.5 mm/h when $P(t) \geq 0.5$ mm/h and $I(t) = P(t)$ when $P(t) < 0.5$ mm/h. The total AET (AET′), which we from here on simply refer to as AET, will also depend on the intercepted rainfall in the canopy $I(t)$.

$$\mathrm{AET}'(t) = \mathrm{AET}(t) + I(t) \tag{2}$$

Positive values of $\frac{d\theta(t)}{dt}$ due to infiltration and hydraulic redistribution of soil water are neglected for periods between the beginning of a rainfall and 2 h after its end. Under these conditions we assume that AET(t) is equal zero. As the time scale of infiltration and redistribution after a storm is smaller than the second time of $\Delta t = 1$ day that was

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tested and for which the soil water content was averaged over 24 h, the impact of summer storms will be implicitly included in the water balance calculations with the longer model time step.

For model validation, observed AET from the flux towers was used. To assess the sensitivity of the estimates to the different model choices, modeled and observed AET were compared at different levels of aggregation:

- mean total summer AET over the study period
- mean diurnal cycle
- mean evolution of AET over the course of the summer season (10 day averages)

Futhermore, the sensitivity to the inter-annual climatic variability was assessed based on annual total summer AET as well as on Nash-Sutcliffe efficiency indices (Nash and Sutcliffe, 1970) for the simulated time series of each summer.

4 Results

4.1 Sensitivity to model and time step

Table 2 shows the total summer AET observations and summer AET estimates from the models for the period from 2001 to 2008 at the young stand (YS) and mature stand (MS) and for the period from 2002 to 2008 at the intermediate stand (IS). The observed summer AET increases with stand age while its standard deviation (in parentheses) decreases. Using a model step of 30 min, Model I slightly underestimated AET at the YS, moderately underestimated AET at the IS, and slightly overestimated AET at the MS. Model II consistently overestimated AET, moderately at YS and IS and considerably at MS. The difference between observations and simulations ranged from 3 to 14% of total summer AET, with an exception of 28% when accounting for interception at the MS. Despite higher standard deviations in the modeled AET, Model I provided the best

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AET estimates. Using a model step of 1 day results in unrealistically low ET estimates, which amount to only about half the observed AET. The results for both models were the same for the 1 day time step.

Figure 1a and b show the mean diurnal cycle of observed and simulated summer AET from 2001 to 2008 using $\Delta t = 30$ min and the two different models. AET is generally underestimated during daytime: slightly at the young stand (YS) and mature stand (MS), but strongly at the intermediate stand (IS). AET is overestimated during nighttime, again most strongly at IS, where the AET observations show a weaker diurnal variation than at the other stands. The effect of interception (Fig. 1b) does not considerably improve the simulations. With the exception of the YS, the observed soil moisture drydown during nighttime does not reflect the strong reduction of latent heat fluxes during the night.

Using the same modeling time step of $\Delta t = 30$ min, Fig. 1c and d show the observed and simulated mean 10-day summer AET from 2001 to 2008. The results from Model I (Fig. 1c) show a strong underestimation in early to mid summer and a slight overestimation of AET in late summer. When accounting for interception (Fig. 1d) AET at IS and MS is overestimated more strongly during the second half of the summer period when autumn storms start to occur.

AET prediction was found to be more sensitive to the computational time step than to the choice of the model. The soil water balance calculation with a data aggregation to daily soil water contents shown in Fig. 1e resulted in a substantial underestimation of AET for all stands, especially during the first part of the summer. For the computational time step of 1 day the precipitation time series were also aggregated to daily values. In this case accounting for interception did not have any influence on these results as the mean daily rainfall intensity in summers within this region lies below Gash's interception threshold. However, the percolation caused by the sporadic rainfall events reduced the amount of water soil depletion and consequently the estimation for summer AET.

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4.2 Interannual variability

Observed summer AET shows considerable inter-annual variability with differences along the chronosequence: AET at the YS and IS generally varies more from year to year than AET at the MS (Fig. 2, Table 2). For the different stands the performance of the model also shows a different sensitivity to this climatic variability. The summers in 2003 and 2006 were dry compared to historical observations while 2004 and 2007 were wet summers. Figure 2 shows that the observed AET in those years and the simulated ET at the YS and IS followed the expected variation of AET from a dry to a wet summer and subsequently to a dry one. The behavior at the MS was more complex. The soil water balance indicates an increase in AET until the occurrence of the extreme dry summer of 2003 and then started a steady decrease until 2008 despite the subsequent wet summers.

The inclusion of interception $I(t)$ (Model II) has hardly any effect on the magnitude and interannual variability of AET at the YS. However, at the IS Model II improved the prediction of AET during five years out of six. Explaining the larger standard deviation of annual AET for Model II at the IS, Fig. 2 illustrates that the larger interannual variability is closer to the interannual variability of the observations. At the MS Model II shows no improvement of the representation of interannual variability and increases the overestimation of Model I with the exception of the last two years.

In a similar way, the model performance can be summarized by the Nash-Sutcliffe efficiency index (NS) calculated from the half-hourly values for each summer period. The indices revealed considerable variation among years (Fig. 3). However, the NS values are overall high. At the young and mature stands they were mostly above 0.7 while at the intermediate-aged stand they were mostly in the order of 0.6. They are proof for the predictive power for diurnal AET estimates as the NS values is biased to the high values of a time series. The drought summer in 2003 presents an outlier with a negative NS for the mature stand. The effect of drought may also have had a lagged effect on the modest results at IS in 2004. However the ability of the model to capture

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AET patterns at YS and MS recovered during the subsequent years. At the YS the model approach seems most resilient to seasonal drought.

5 Discussion

We showed that summer soil moisture depletion at the point scale can be used to estimate summer AET at the footprint scale as observed with eddy-flux measurements. The stand age at different stages of succession did not systematically affect the agreement between the observations and model estimates in most years and for the mean. Interannual climatic variability somewhat affected the estimates. The response of the soil moisture balance to the interannual variability was consistent and proportional to the observed changes in the summer AET, but appeared to show a closer coupling for the young and intermediate stands. In the mature stand summer AET shows little interannual variability and during an extreme dry year, AET for the mature stand appeared decoupled from soil moisture in the top soil layer.

The increase of the mean and the decrease of the standard deviation of summer AET with stand age, suggests that summer AET is more sensitive to climatic variability for early successional stages than for mature and old forest stands. A potential improvement of the modeled AET through the consideration of rainfall interception for predicting summer AET was inconclusive. However, the choice of a computation step of $\Delta t = 30$ min and an active root depth $Z_r = 30$ cm proved superior to other model options. Larger computation time steps as $\Delta t = 1$ day imply that the effects of recharge during rainfall events are taken in account so it can notably reduce root water uptake and hence underestimate summer AET by more than 50% according to field observations. The negligence of tree rooting strategies during periods of water stress by using soil moisture from a fixed root depth of 30 cm for the model resulted into an overestimation during extreme dry years at the mature stand. The incorporation of soil water to root depth dynamics may reduce the error (Teuling et al., 2006a; Schymanski et al., 2008), but requires at least one free parameter.

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The analyzed 2300 days in total over 8 years was longer than that of previous studies and hence possibly lead to more conclusive results. For instance, Schwärzel et al. (2009) analyzed the spatial heterogeneity of soil moisture to predict AET in two forest stands during a growing season characterized by an exceptional drought. Although the initial results were satisfactory, the total AET was underestimated by the end of the season. In a similar approach, Schelde et al. (2010) found consistent results at the end of spring that contrasted large devations at the beginning of summer. In these studies, the computational time step Δt and root active layer Z_r was 60 min and a layer averaged over 6 different depths between 5 and 90 cm in Schwärzel et al. (2009), and 1 day and 75 cm in Schelde et al. (2010), respectively. Schelde et al. (2010) showed from an agricultural field that despite different initial conditions soil water depletion, and hence AET was similar. Such similar behavior in water uptake by roots and evaporation from the soil contrasts with the differences observed in soil water depletion rates along the successional chronosequence.

6 Conclusions

The parsimonious data-driven model for the estimation of summer AET presented here has a main advantage over more data-intensive modeling schemes to study hydrological changes in recovering forested ecosystems. For example, LAI, soil properties, resistivity and root depth parameterization are not required. The current approach proved to be useful for predicting evapotranspiration during the water limited period of the year in a disturbed and successional temperate ecosystem and its differences in their magnitude caused by different patterns of interception, soil evaporation and transpiration. An eight-year comparison of both models' output showed that in order to provide acceptable AET estimates it is essential to account for rainfall in the soil water balance by choosing an adequate calculation time step. An implication of these results may be the possibility that AET could be derived from soil moisture depletion using large computation time steps in other ecosystems with limited precipitation during the

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growing season). The results provided here showed that one single model structure is sufficient to make a first-order estimate of hydrologic change in a gradually evolving landscape and thus does not constitute a problem for modeling purposes (e.g. Schaefli et al., 2011). However, the model should be tested across a wide range of forested and non-forested landscapes in different climates to evaluate applications including estimates at sites where eddy covariance measurements are limited or difficult due to topographic complexity, where long-term soil moisture data are available and for large-scale catchment water balance assessments using remote-sensing techniques.

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Table 1. Characteristics of the successional forest chronosequence experimental sites in Campbell River, Canada.

	Young stand	Intermediate stand	Mature stand
Abbreviation	YS	IS	MS
Year of establishment	2000	1988	1949
Latitude	49°52′20″ N	49°31′11″ N	49°52′8″ N
Longitude	125°17′32″ W	124°54′6″ W	125°20′6″ W
Elevation (masl)[a]	175	170	300
Tree Height (m)[a]	2.4	7.5	33
Stand density (stands/Ha)[a]	1400	1200	1100
LAI (–)[a]	1.1	5	7.3
Mean annual AET (mm)[a]	253	362	398
Mean summer AET (mm)	126	161	168

[a] from Jassal et al. (2009).

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Table 2. Observed and modeled mean total summer AET (mm) for the period 2001–2008. Standard deviation (mm) is in parentheses and absolute error (%) is in brackets.

Stand	Observed	$\Delta t = 30$ min		$\Delta t = 1$ day
		Model I	Model II	Model I / Model II
YS	129 (23)	121 (46) [6]	133 (47) [3]	73 (24) [43]
IS	159 (22)	136 (28) [14]	170 (38) [7]	63 (13) [60]
MS	167 (13)	177 (44) [6]	207 (39) [24]	96 (28) [43]

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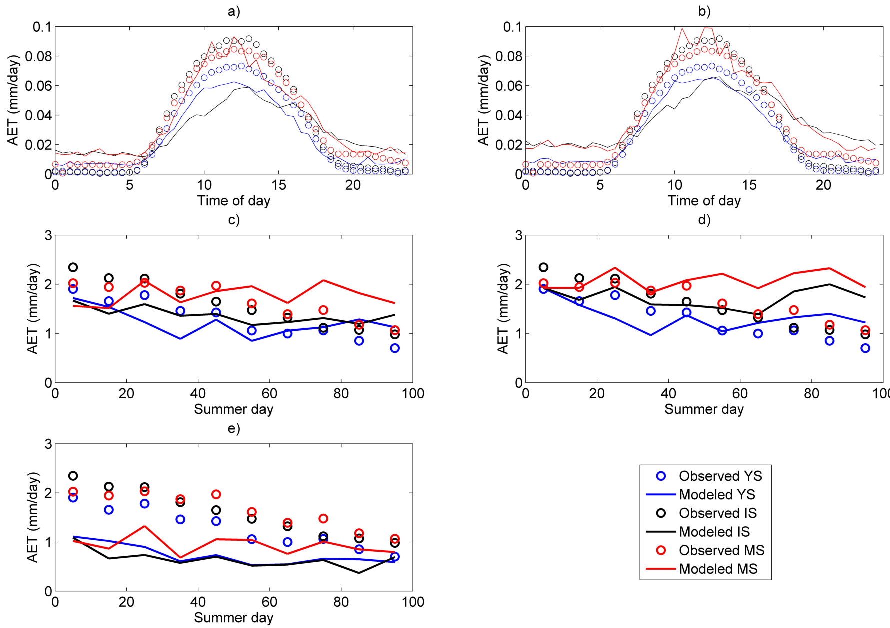

Fig. 1. Modeled and observed summer AET (2001–2008) based on $Z_r = 30$ cm: **(a)** mean diurnal cycle simulated with Model I at $\Delta t = 30$ min, **(b)** mean diurnal cycle simulated with Model II at $\Delta t = 30$ min, **(c)** mean 10-day moving daily values simulated with Model I at $\Delta t = 30$ min, **(d)** mean 10-day moving daily values simulated with Model II at $\Delta t = 30$ min, and **(e)** mean 10-day moving daily values simulated with Model I at $\Delta t = 1$ day.

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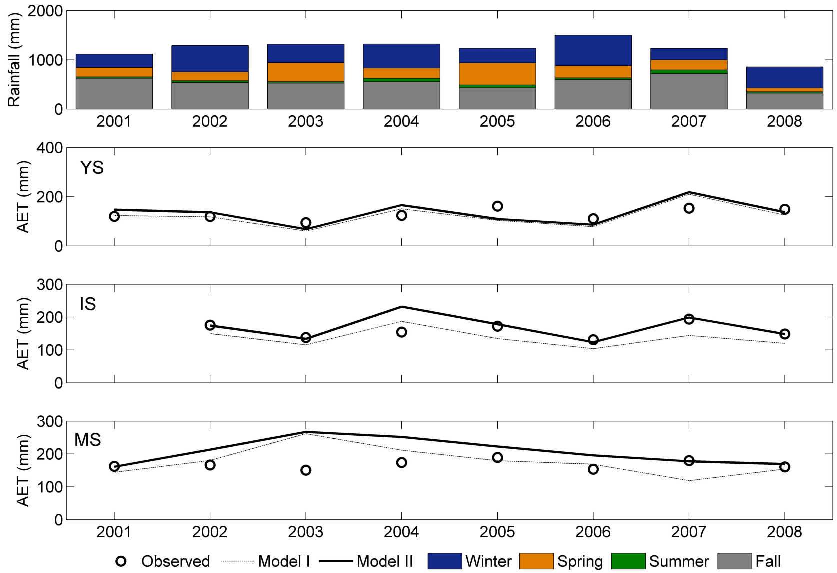

Fig. 2. Inter-annual variability of seasonal precipitation (top) and, observed and modeled summer AET at the different successional forest stands. AET modeled with $\Delta t = 30$ min.

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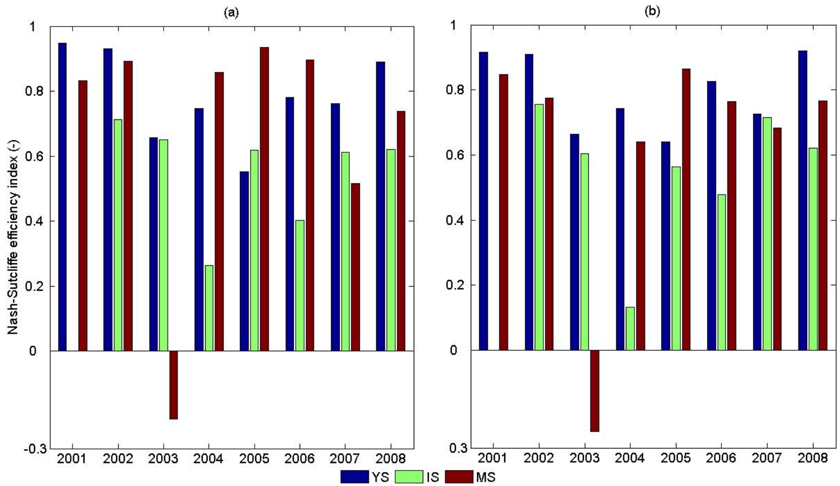

Fig. 3. Nash-Sutcliffe efficiency for seasonal simulations with **(a)** Model I and **(b)** Model II. AET modeled with $\Delta t = 30$ min.

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