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How to predict hydrological effects of local land use change: how the vegetation parameterisation for short rotation coppices influences model results

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How to predict hydrological effects of local land use change

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Abstract

Among the different bioenergy sources short rotation coppices (SRC) with poplar and willow trees are one of the mostly promising options in Europe. SRC not only provide woody biomass, but often additional ecosystem services. One known shortcoming is the possible negative effect on groundwater recharge, caused by potentially higher rates of evapotranspiration compared to annual crops. An assessment of land use change by means of hydrological models and taking into account the changing climate can help to minimize negative and maximize positive ecological effects at regional and local scales, e.g. to regional climate and/or to adjacent ecosystems. The present study implemented the hydrological model system WaSim for such assessment. The hydrological analysis requires the adequate description of the vegetation cover to simulate the processes like soil evaporation, interception evaporation and transpiration. The uncertainties in the vegetation parameterisations might result in implausible model results. The present study shows that leaf area index (LAI), stomatal resistance (Rsc) as well as the beginning and length of the growing season are the sensitive parameters when investigating the effects of an enhanced cultivation of SRC on water budget or on groundwater recharge. Mostly sensitive is the description of the beginning of the growing season. When this estimation is wrong, the accuracy of LAI and Rsc description plays a minor role. The analyses done here illustrate that the use of locally measured vegetation parameters like maximal LAI and meteorological variables like air temperature, to estimate the beginning of the growing season, produce better results than literature data or data from remote network stations. However the direct implementation of locally measured or literature data on e.g. stomatal resistance is not always advisable. The adjustment of locally vegetation parameterisation shows the best model evaluation. Additionally the adjusted course of LAI and Rsc is less sensitive to different estimates for leaf unfolding, due to a slower increase in spring compared to a step functional annual course.

1 Introduction

In the scope of climate change mitigation and reduction of greenhouse gases (GHGs) emissions bioenergy is one of the possible alternatives for fossil fuels. Among the different bioenergy sources short rotation coppices (SRC) with mainly poplar and willow trees are one of the mostly promising options in Europe. SRC not only provide woody biomass, but also additional ecosystem services. Additionally seepage water quality is enhanced, due to lower fertilizer requirements and higher nutrient use efficiency (Aronsson et al., 2000; Schmidt-Walter and Lamersdorf, 2012). Compared to conventional annual crops SRC sequester more carbon and emit less N_2O (Don et al., 2012), which is one of the most important GHGs. As structural landscape elements in rural areas SRC might also contribute positively to biodiversity (Baum et al., 2012). Yet SRC are not without some disadvantages.

One known shortcoming is the possible negative effect on groundwater recharge (GWR), caused by potentially higher rates of evapotranspiration in poplar and willow plantations compared to annual crops (Lasch et al., 2010; Schmidt-Walter and Lamersdorf, 2012). An assessment using hydrological models can help to minimize negative and maximize positive ecological effects at regional and local scales, e.g. to regional climate and/or to adjacent ecosystems. To provide an adequate assessment the hydrological models require the corresponding parameterization of land use including vegetation. The planting of SRC causes the occurrence of new factors and complex factor interactions influencing site water fluxes. One factor is the all year vegetation cover with higher leaf area index (LAI, $m^2\,m^{-2}$) in combination with a longer growing season comparing to annual crops (Petzold et al., 2010).

LAI has a control on transpiration and additionally influences soil evaporation and interception evaporation. Furthermore the latter is increased by the interception from stem and branches, especially outside of the growing season. Other important parameters controlling the water balance are the stomatal resistance (Rsc), rooting depth and roots distribution. The structural and biophysical parameters, however, do not remain stable during the year, but have a seasonal or even annual course. The most intensive changes occur during the growing period. Thus, the beginning and length of the growing season should be known to adequately describe the seasonal dynamic of vegetation parameters in hydrological modelling.

The smaller the scale of interest the more detailed time-dependent parameterisation of land use and vegetation is necessary to capture the spatial and temporal variability of effects. There are two possibilities to obtain the required information: the first one, the labour- and time-consuming way, is to measure the parameters like LAI or Rsc directly at the investigated site. The other possibility is to apply parameters from scientific literature. This information is quite rare for SRC, due to the fact that this land use scarcely came into focus of investigation as a part of the renewable energy discussion during the last years (Surendran Nair et al., 2012). Very often not the annual course, but only one value is given, e.g. the maximum value for LAI, or the minimum value for Rsc, describing together the maximum transpiration. In such cases the annual course for these parameters has to be estimated for hydrological modelling. Of course the question on transferability of published results obtained in a certain area and year to other regions and years has to be solved in each study separately. However, it is well known that neither literature values nor direct measurements provide the true values of model parameters, but more or less representative approximations, because of spatial and temporal heterogeneity of vegetation stands including SRC.

In this study we used the results of our own measurements of LAI, Rsc and the estimation of leaf unfolding date, determining the beginning of growing period, for a poplar SRC to parameterise the hydrological model system WaSim (Schulla and Jasper, 2013). The aim of present study is to assess the effect of parameterisation uncertainties of the land use type poplar SRC on modelling results. The hypothesis, that the parameterization of LAI, Rsc and the beginning of growing period based on measurements shows a better model fit than the use of literate values in combination with approximation about the annual course should be proofed.

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2 Material and methods

2.1 Study site

The most extensive investigations were carried out at the study site Reiffenhausen (51.67° N, 10.65° E, 325 m a.s.l.), located south of Göttingen, central Germany. According to the meteorological data provided by the German Weather Service (Deutscher Wetterdienst, DWD), for the station Göttingen (DWD Station-ID: 01691), nearest to the study site, the climate is characterized by an average temperature of 9.1 °C (±0.7 °C) and a mean annual precipitation sum of 635 mm (±122 mm) for the period 1971–2010.

The soil is characterized by a sedimentary deposits of Middle and Upper Buntsandstein, like sandstone, siltstone and clay stone. The main soil types present at the field level are stagnic cambisol and haplic stagnosol with a soil quality (Ackerzahl) of approximately 45 points. The maximum available points are 100 for very good agriculture fields (Blume et al., 2010). The soil texture is dominated by loamy sand or silty clay.

The plantation Reiffenhausen was established at a former arable field in March 2011 with the poplar clone Max1 (*Populus nigra* × *Populus maximowiczii*). The poplar SRC were planted with 0.2 m long cuttings on 0.4 ha in a double row system with alternating inter-row distances of 0.75 and 1.50 m, and a spacing of 1.0 m within the rows, yielding an overall planting density of 8800 cuttings per hectare. A detailed site description, including soil chemistry and biomass information is given by Hartmann et al. (2014). In 2011 the weather conditions at Reiffenhausen were unfavourably dry for the initial growth after planting. During the first months in 2011, from February to May, the precipitation sum was unusually low – only 42 % of the long term (1971–2010) precipitation (78 of 188 mm for the long term mean). This led to dry soil conditions, especially in the upper soil, and resulting in a survival rate of only 63 % for the poplar SRC. In 2013, when the most measurements and investigations took place the poplar SRC reached a height of 5–6 m, indicating that the unfavourable initial conditions were somewhat improved. The poplar SRC was fully developed in hydrological terms. The development of the rooting system was eventually enforced by the dry conditions during the initial phase (Broeckx et al., 2013). Rooting depth was more than 1 m in the second year after planting, exploiting the main part of soil layer above the bedrock (Kalberlah, 2013). The LAI reached 5 $m^2 m^{-2}$ in 2012 and 6–7 $m^2 m^{-2}$ in 2013, which is typical for a fully grown poplar SRC (Schmidt-Walter et al., 2014). Comparing to another poplar SRC nearby established in 2012 under more favourable initial conditions, the poplars in Reiffenhausen are characterized by a higher share of woody material (more branches) and somewhat smaller but numerous leaves.

Observations for leaf unfolding are also used form the site Großfahner, which is also part of the BEST-research project. Großfahner is located near Erfurt, Thuringia, Germany and was also established in 2011 with the poplar clone Max1 (Hartmann et al., 2014).

2.2 Measurements

2.2.1 Micrometeorological and local soil measurements

In Reiffenhausen the micrometeorological measurements were carried out in the centre of the SRC stand, the instruments were installed above the vegetation on a 10 m mast. The air temperature and humidity were measured using Hmp45C (Campbell Sci.; Loughborough, UK); wind speed and wind direction (wind sensor compact and wind direction sensor compact, both ThiesClima; Göttingen, Germany), atmospheric pressure (pressure sensor, Theodor Friedrichs & Co.; Schenefeld, Germany) and solar radiation (CMP3, Kipp & Zonen, Delft, the Netherlands) were measured continuously with 1 Hz frequency and averaged over 15 min. 5 min precipitation sums were obtained using an ombrometer (Precipitation Transmitter, ThiesClima; Göttingen, Germany). The values were averaged and stored by a CR1000 data logger (Campbell Sci.; Loughborough, UK). Additionally to the meteorological measurements in the centre of the poplar SRC, a reference station was similarly equipped and installed approximately 500 m to the north from the stand in the open place (short-grass meadow) to measure the climate variables unaffected by the poplar SRC.

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The soil moisture was measured continuously every 15 min using tensiometers and soil water content probes in 20, 60 and 120 cm depth, by six (tensiometers) and three (probes) sensors in every depth. Tensiometers were constructed in the Department of Soil Science for the study using the PCFA6D pressure sensor (Honeywell; Morristown, NJ, USA) and a P-80 ceramic (CeramTec AG; Marktredwitz, Germany). Volumetric soil water content and soil temperature were measured using SM-300 probes (Delta-T Devices Ltd; Cambridge, UK). Additionally, descriptions of soil horizons and soil texture were assessed using a soil pit near the SRC.

Additionally to the data of Reiffenhausen, meteorological data and data of phenological observations from Tharandter Wald (Tharandt Forest) are used. The Tharandter Wald is the biggest contiguous woodland in the federal state Saxony (Germany) being located 15 km southwest of city of Dresden. Geologically, the Tharandt Forest is part of the forelands of the Ore Mountains. The climate of this region can be classified as sub-oceanic. The average annual temperate and the average annual total of precipitation are 7.2 °C and 850 mm respectively measured in the centre of Tharandter Wald at climate station Grillenburg, climate period 1961–1990 (Spank, 2010).

The Technische Universität Dresden (University of Technology Dresden) operates numerous test sites and outdoor laboratories within the Tharandter Wald as well as in its near vicinity (Bernhofer, 2002; Spank, 2010; Spank et al., 2013). In frame of this study, data of the International phenological garden Tharandt-Hartha (IPG), being located at eastern edge of the Tharandter Wald (50.59° N, 13.32° E, 360 m a.s.l.), have special importance. The IPG was established by initiative of creation of a standardized European phenological monitoring network in 1959 (Volkert and Schnelle, 1968). A complete site description as well as detailed information about observation standards and monitored species can be found in Seidler (1995).

Meteorological variables (air temperature, air humidity, precipitation, wind speed at 2 m height and incoming solar radiation) are measured at this site only since May 2005. However, two neighbouring sites (Wildacker and Grillenburg), being located in distance of approximately 3 km away from IPG, provide meteorological and climatological information since 1958. The station Wildacker belongs to the micro-meteorological and silvicultural outdoor laboratory Anchor Station Tharandt Forest. The site Wildacker is located on a small clearance in a coniferous forest. It was established to provide open land information for comparison with internal forest climate being measured at the Anchor Station Tharandt Forest. In contrary to that, the station Grillenburg represents a standard climate station. This site fulfils all World Meteorological Organisation guidelines and standards for large-scale representative climatological measurements.

2.2.2 Leaf area index

For the present study we use the definition of leaf area index by Watson (1947) cited in Breda (2003) as the total one-sided area of leaf tissue per unit ground surface area with the dimension of $m^2\,m^{-2}$ (or dimensionless). There are numerous ground-based as well as remote sensing-based techniques to estimate LAI. An extensive overview of ground-based methods is given by Breda (2003). Direct methods: allometric, litter collection and harvesting are based on statistically significant sampling of phytoelements and phytoelement dimensions. Among them only the harvesting can provide the information on the seasonal dynamic of LAI for the whole season or year. The obvious disadvantages of harvesting as destructive method, however, are that it is very time- and labour-consuming, that the canopy is irreversibly damaged and further statistically representative LAI-measurements for seasonal dynamics are affected.

Indirect ground-based methods are non-destructive and based on the inversion of the Beer–Lambert law, i.e. on measurements of the extinction of short-wave solar radiation by the canopy. The extinction is related to the vegetation structure parameters including LAI (Eq. 1).

$$\mathrm{LAI} = \frac{\ln\left(I/I_0\right)}{k} \quad \text{with} \quad k = \frac{G(\Theta,\alpha)}{\cos\Theta} \tag{1}$$

where LAI is the leaf area index for the vegetation layer, I_0 is the radiation intensity incident to the vegetation layer, I – radiation intensity at the lower bound of vegetation

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layer and k is the extinction coefficient (Breda, 2003). The function G is the projection of unit foliage area on the plane normal to the direction Θ, Θ – zenith angle and α is the leaf angle distribution. It should be also noted that indirect methods estimate not LAI but Plant Area Index (PAI) as the light attenuation is caused not only by leaves but by branches and tree stems as well. To derive LAI either the correction factors are applied which subtract the share of woody material from PAI, or the assumption is made (especially for dense canopies) that the attenuation is caused for the most part by leaves. The underlying assumptions, e.g. on stand homogeneity and small black opaque phytoelements that have to be considered to ensure the applicability of indirect methods, as well as advantages and disadvantages of various methods are presented, e.g. in LAI2000 Manual (LI-COR INC, 1992), in Breda (2003) and Jonckheere et al. (2004).

For the present study the data of one direct and two indirect methods for the estimation of LAI of the poplar SRC in Reiffenhausen were used. For the indirect method we used two different types of instruments. First – two LI191SA Line Quantum Sensors (LI-COR Inc., USA) were used to measure incident ($I_{0,\mathrm{PAR}}$) and within-stand photosynthetic active radiation (I_{PAR}) to calculate the LAI using Eq. (1). The $k = 0.5$ for mixed broadleaved species was chosen in our study (Breda, 2003). Second – two plant canopy analysers LAI2000 (LI-COR Inc., USA) were implemented in Two-Sensor mode (LI-COR INC, 1992) to obtain LAI and k. Measurements were performed weekly whenever possible from May till November 2013 under homogenous illumination, i.e. at days with overcast conditions or during morning or evening hours. Sensor pairs were cross-validated at the beginning of each measurement day.

In the homogeneous poplar SRC ten evenly distributed plots were selected. To account for the double row planting of the SRC 3 m × 3 m square grids with 1 m distance between grid points were marked at every plot so that 16 grid points per plot were obtained for measurements. At each grid point two measurements were performed with instrument oriented along and perpendicularly to SRC rows. Thus 32 measurements were performed at each of ten plots during every measurement day.

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To obtain the reference values for leaf area the direct destructive sampling-harvesting were carried out. All phytoelements within the square column of 1 m^2 surface area were collected and measured with leaf area meter (LI-3100; LI-COR Inc., USA). The sampling was carried at 26 August 2013 at three plots within the investigated stand.

2.2.3 Stomatal resistance

The dominant factor controlling both the water loss from plant leaves and the uptake of CO_2 for photosynthesis is the resistance of stomata, regulated by the plant in response to environmental conditions. Stomatal resistance, or it's reciprocal the stomatal conductance, is an important parameter in hydrological modelling, controlling the rate of transpiration for the different vegetation types. The version of WaSim applied in present study uses the Penman–Monteith approach for calculating evapotranspiration and requires a parameter of minimal surface resistance for a state when plants are fully supplied with water (Schulla, 1997; Schulla and Jasper, 2013).

For the Rsc measurements in poplar SRC we used the SC-1 leaf porometer (Decagon Devices Inc.; Pullman, WA, USA). The measurements took place in Reiffenhausen in 2013 and were carried out every week from May till September only under favourable weather conditions promising minimal resistances: preferable sunny, but at least without rain and with dry leaves. The same 10 locations in the poplar SRC as for the LAI measurements were used and so called sun-leaves were marked to measure the same leaf at different times. All 10 locations were measured during one hour to minimize the effects of changing weather conditions. Measurements were started in the morning, when leaves are dry and continued till afternoon, or as long as weather conditions were appropriate.

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2.2.4 Phenology – start of growing season

Phenological phases of plants, such as leaf unfolding and leaf colouring of trees are mainly driven by environmental factors but also by soil conditions, plant provenance and age (Menzel, 2000).

Within WaSim a modified approach for estimating leaf unfolding date according to Cannell and Smith (1983) is implemented and used here. A detailed description of this model as presented in Eqs. (2)–(5), as well as parameterisation examples (Table 1) is given by Menzel (1997).

The model has four parameters: T_0, T_1, a and b which are the threshold temperatures for chilling units and for forcing units and two tree specific regression parameters, respectively. The starting day for leaves unfolding is calculated according to Eq. (2).

$$T_\mathrm{S} = \sum_{i=0}^{n} \begin{cases} T(t_1 + i\Delta t) - T_1 & T(t_1 + i\Delta t) \geq T_1 \\ 0 & T(t_1 + i\Delta t) < T_1 \end{cases} \quad (2)$$

Here T_S is the temperature sum, T is the daily mean temperature for a day $t_1 + i\Delta t$, t_1 is set as 1 February in present study and time step, Δt, as one day. The daily mean temperature is calculated according to Eq. (3).

$$T = \frac{T_\mathrm{min} + T_\mathrm{max}}{2} \quad (3)$$

Here T_min is the daily minimum temperature and T_max the daily maximum temperature. The leaf unfolding occurs when T_S reaches the critical value $T_\mathrm{S,crit}$ (Eqs. 4 and 5).

$$T_\mathrm{S,crit} = a + b\ln(\mathrm{CD}_n) \quad (4)$$

with

$$\mathrm{CD}_n = \sum_{i=0}^{n} \begin{cases} 1 & T(t_0 + i\Delta t) \leq T_0 \\ 0 & T(t_0 + i\Delta t) > T_0 \end{cases} \quad (5)$$

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CD is the number of chilling days, i.e. when $T < T_0$, between days t_0 and t_1. The date t_0 was set as 1 November in present study. Values for T_0, T_1, a and b for *Populus tremula* (IPG235) are given by Menzel (1997) (Table 1).

Using these numbers as initial values we fitted the parameters T_0, T_1, a and b to observed dates of leaf unfolding for the poplar clone Max1 in Reiffenhausen for the years 2012 and 2013 using least squares method. Finally we evaluated the obtained model parameters against the independent observations in Reiffenhausen (for 2014), against observation in Großfahner for the years 2012 and 2013 (Lorenz and Müller, 2013) and 2014 (K. Lorenz, personal communication, 2014). The observed date of leaf unfolding in Reiffenhausen and Großfahner is comparable to the recommendations according to Volkert and Schnelle (1966).

For comparison the data from the international phenological observation networks (IPG) are used (Chmielewski et al., 2013), namely the leaf unfolding date of *Populus tremula* (IPG235) at the IPG station Tharandt-Hartha. The phenological phase of leaf unfolding is defined as the stage UL, according to the IPG webpage (International Phenological Gardens of Europe, 2014) and is obtained by daily observations of plant's development state. The IPG station Tharandt-Hartha is located at the eastern border of the Tharandter Wald (50.59° N; 13.32° E; 360 m a.s.l.). It is the nearest IPG station to the site Reiffenhausen, and comparable in altitude. This IPG station was established in 1959 by the initiative to create a standardized European phenological monitoring network (Volkert and Schnelle, 1968). A list about species and phenological items, being monitored at this site, as well as a comprehensive description of station's history is offered by Seidler (1995).

2.3 Modeling approach

For simulation, the deterministic spatially distributed hydrological catchment model system WaSim (version 9.05.04) was used. Complete and comprehensive descriptions of this model and its internal structure can be found inter alia in Schulla (1997) and Schulla and Jasper (2013). The setup of physically based parameters, such as LAI and Rsc as

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well as phenological state (date of leaf unfolding here), are predicated on direct measurements and observations. Thus, physical nexus between model image and reality is reproduced as best as possible. The SRC described with these measurements and observations represents an approx. 3 year-old poplar SRC, which can be seen as a hydrological fully developed canopy, concerning LAI, Rsc and root development. The simulated local soil water contents were compared and evaluated with measurements.

Different model simulations are done to show the suitability of the direct use of specific plant physiological measurements, as well as the effects of an approximated parameter description in the model, i.e. the annual course and the quantity of LAI, Rsc and phenology.

All these model approaches were done on a plot model domain, which are 3 × 3 raster cells based on a digital elevation model with a spatial resolution of 12.5 m (LGLN – Landesbetrieb Landesvermessung und Geobasisinformation, 2013), provided by the project partner NW-FVA[1]. All topographic information, needed by the model is derived by the model itself. The research site, providing the measured soil water contents for model calibration is located in the centre of the domain. A retention curve required in hydrological modelling for the description of soil physical properties was taken from Van Genuchten (1980). The Van Genuchten retention parameters from Blume et al. (2010) were chosen, based on a characterization of soil texture and soil horizons in Reiffenhausen.

The meteorological forcing data were taken from own measurements for the period 2011–2013, whereas the first two years were used for the model spin up. Analyses and the evaluation with measured local soil water contents were done for the year 2013, only. To show the effects of different parameterisations under various climate conditions the simulations were performed for the period of 1969 to 2013 using the forcing meteorological data from DWD station Göttingen. The period was chosen as the longest period without missing values. The parameterisation of land use is kept

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constant for the whole period. A WaSim control file including all information about parameterization and model setup in provided as Supplement.

2.4 Data analysis

All measured and applied meteorological, soil physical and eco physiological parameters have been checked for measurement errors and plausibility before being analysed or used for modelling.

The data has been numerically analysed and graphically presented with the free software package GNU Octave, version 3.6.2 (Octave community, 2012). Parts of the statistical analysis were performed using the hydroGOF package (Mauricio Zambrano-Bigiarini, 2014) within the R software environment (R-Studio under Windows, version 0.98.501) for statistical computing and graphics (R Development Core Team, 2011).

Criteria for the quantification of model performance were chosen according to Moriasi et al. (2007).

The Nash–Sutcliffe model efficiency criterion (NSC), the percent bias (PBIAS), and the ratio of the root mean square error of the standard deviation (SD) of measured data (RSR) were calculated and used to determine a sufficient model evaluation.

3 Results

3.1 Measurements

3.1.1 Leaf area index

Figure 1 shows the annual course of LAI, derived from two different indirect optical and one direct destructive method. Leaf unfolding started shortly before the first measurement at the 1 May 2013. Until the 1 August there is almost a linear increase of LAI up to 7.3 and 5.5 for the LI191SA and the LAI2000 measurements, respectively. Maximal observed values out of all 160 measurements are 10.5 and 6.5 $m^2\,m^{-2}$, respectively

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(not shown). After that LAI starts to decrease, with a more rapid decline toward the end of August 2013. Leaf fall was almost finished at the 25 October.

Differences between devices, i.e. LI191SA vs. LAI2000, are large. The LAI values obtained with the LI191SA are systematically $\approx 2\,m^2\,m^{-2}$ higher. The values obtained by direct destructive sampling at the 26 August are rather on the level of the LAI2000 estimates.

3.1.2 Stomatal resistance

Figure 2 shows the stomatal resistance (Rsc) as measured on well illuminated leaves at the poplar SRC Reiffenhausen in 2013. Values are ranging from 100 to 300 $s\,m^{-1}$ until August 2013. At the 18 June Rsc is higher with larger SDs as the previous measurement at the 14 June. Soil water supply is sufficient on both days. The two days significantly differ in temperature, although the 14 June is relatively colder with a daily maximum temperature of approximately 17 °C and the 18 June is quite hot, reaching a maximum temperature of 33 °C. Starting from August both mean Rsc and SD are steadily increasing. This period is characterized by decreasing soil water availability leading to severe drought stress conditions. Due to higher Rsc the trees counteracting the drought stress to avoid water loss and xylem damage, e.g. embolism of xylem vessels. The increase of SD is an expression of stand heterogeneity, single trees still have access to water, and other may already be limited or stressed. In September 2013 we stopped measurements because leaves were visibly affected by the drought stress event. The correlation of plant available soil water and plant regulation via stomata seems to be consistent, increasing confidence in the distinct measurements. The minimum observed stomatal resistance is 80 $s\,m^{-1}$.

3.1.3 Phenology – start of growing season

We used phenological observations of the two years 2012 and 2013 in Reiffenhausen to calibrate the modified approach for estimating the date of leaf unfolding according

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to Cannell and Smith (1983), which is used in WaSim. In 2012 leaf unfolding for Max1 in Reiffenhausen started at day of year (DOY) 88, i.e. the 28 March 2012 (Table 2). In 2013 leaf unfolding was delayed by approximately 4 weeks due to low temperatures in spring and started at DOY 115 (25 April 2013). Our calibration resulted in values of 10 and 2 °C for T_0 and T_1. The regression parameters a and b are 2200 and −403, respectively (Table 1). Estimates of leaf unfolding using these values for T_0, T_1, a and b show deviations to the observed dates of +3 and −3 days for Reiffenhausen in 2012 and 2013, respectively. Then the phenological model results with the obtained parameter set and local temperatures were compared to phenological observations in Reiffenhausen in 2014 and in Großfahner in 2012 and 2013. Observed dates of leaf unfolding in Großfahner are almost equal to that in Reiffenhausen, also showing the delay of approx. 4 weeks in 2013 compared to 2012. The phenological model using the Max1 parameters result in differences of −1 day for Reiffenhausen in 2014 and of −1 and −2 days for Großfahner in 2012 and 2013 compared to observations. Table 2 also shows the application of the IPG235 parameter set provided by Menzel (1997) for *Populus tremula*. Parameters of a and b for IPG235 are both smaller in magnitude and threshold temperatures for chilling and forcing units. Due to the wider spread between T_0 and T_1 the model is able to describe extreme values and therefore a higher variability of leaf unfolding, which was observed in 2012 and 2013. The model estimations of the date of leaf unfolding with Max1 and with the IPG235 parameters differ considerably. The IPG235 set produces systematically later dates. Differences to observations are +31 (2012), +10 (2013) and +28 (2014) days for Reiffenhausen and +21 (2012) and +6 (2103) days for Großfahner using the local temperatures (Table 2).

To assess the effects of non-local micrometeorological data sources, the model was driven by temperature measurements from the nearest DWD stations, namely Göttingen for Reiffenhausen and Dachwig for Großfahner. Expectedly, the use of DWD data instead of the local measurements produces mostly larger estimation errors for both the Max1 and the IPG235 parameter set (Table 2).

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We will use the varying parameter sets, i.e. our Max1 model and the IPG235 parameter set (Table 1) to analyse the effect for hydrological modelling for the year 2013, where soil hydrological measurements to evaluate the hydrological model results are available.

To analyse the species-dependence of leaf unfolding date estimations the model with Max1 and IPG235 parameters was also driven by temperature measurements during 2012–1014 at the phenological station Tharandt. Figure 3a–d illustrates that, expectedly, the parameter sets correspond better to the observations at species for which they were calibrated: Max1 parameters to Reiffenhausen and the IPG235 parameters to Tharandt observations, which were part of its calibration dataset. The differences between estimated and observed DOY of leaf unfolding are smaller when local temperature measurements are used. Figure 3e and f show the long term courses of estimated leaf unfolding DOY for Reiffenhausen and Tharandt using the temperatures of the nearest DWD stations (Göttingen and Wildacker). The model with IPG235 is systematically later and shows less variability than with Max1. For Reiffenhausen no long term phenological observations are available. However, the average DOY of leaf unfolding in Reiffenhausen is DOY 97 ± 9 using Max1 and DOY 124 ± 5 for IPG235. The long term phenological observations in Tharandt fit well to the IPG235 estimates, but showing less variability than observed. The average DOY of leaf unfolding in Tharandt as observed is DOY 123 ± 10 days, estimated using Max1 DOY 101 ± 9 days and with IPG235 DOY 124 ± 7 days. In general estimates fit best to observations when the corresponding parameters are used, i.e. Max1 for Reiffenhausen and IPG235 for Tharandt. But variability is underestimated by IPG235 compared to observation.

3.2 Hydrological model simulations

Several model simulations were performed with different parameterisation of LAI, Rsc and leaf unfolding date. Table 3 summarizes the eight performed model simulations and introduces their abbreviations. The detailed descriptions of model simulations are given in the text.

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First the measured values of LAI, Rsc and the start-date of leaf unfolding are implemented for hydrological modelling (LAI2000 Rsc80 and LI191SA Rsc80). Starting from here we changed the parameter sets: (i) to improve the model fit, (ii) to adjust the suitability of applied parameterisations and (iii) to show the effects of different parameterisations on hydrological model results.

3.2.1 Simulation using observed parameters and adaptation of stomatal resistance

First we used the measured annual courses of LAI for hydrological modelling. Rsc is set to the observed minimum of 80 $s\,m^{-1}$, when LAI is larger than 1. The start date of leaf unfolding is not calculated for measured LAI from air temperature using the approach of Cannell and Smith (1983), because this information is already imprinted in LAI measurements and therefore fixed for the year 2013.

Figure 4 shows the applied model parameterisations for LAI and Rsc, as well as the plant available water (PAW), calculated until 1 m soil depth from measured and modelled soil water contents.

For all simulations using the observed value for Rsc (i.e. 80 $s\,m^{-1}$) model results for soil water content were higher than measured values, resulting in a low value of PAW. This is also reflected by the Nash–Sutcliffe criterion calculated from PAW (Table 4). The annual course of PAW is captured quite well by the model, but the drying up in summer is not sufficient, neither for the LI191SA, nor for the LAI2000 measurements. The NSC is better for the experiments with LAI measured by LI191SA (0.69) than with LAI2000 (0.44) because of the higher LAI values (Table 4).

As, especially the maximum of LAI measures using the LAI2000 showed better agreement with direct destructive measurements, we halved the value of Rsc to reach the low PAW values observed. This decision has two reasons. First it can be assumed that the measured Rsc is always higher than the minimum value needed for parameterisation, because the conditions by measuring Rsc are not satisfying the requirements for the parameter to be used in the model, i.e. optimal conditions for transpiration and

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no water stress. Another way to get lower PAW values would be to increase the LAI, as can be seen by comparing the results for LI191SA and LAI2000. However, in our experiment LAI has to be increased to unrealistically high values to minimize the differences to observed PAW. Additionally LAI is also affecting other processes in hydrological models, like interception evaporation and soil evaporation. Together the decrease of Rsc is a consistent way to minimize the deviations to observations and to improve the model fit.

The reduction of Rsc, from 80 to 40 $\mathrm{s\,m^{-1}}$, improved the NSC from 0.69 and 0.44 to 0.89 and 0.87 for the LI191SA and LAI2000, respectively (Table 4).

3.2.2 Approximation and adaptation of annual course of leaf area and stomatal resistance

In many cases when hydrological models should be applied for analyses involving vegetation there are no locally measured data on LAI and/or Rsc. Often only the literature data for the maximum and minimum values of LAI and Rsc are available. Then the annual course for these parameters has to be derived or approximated for modelling. The simplest approximation is a stepwise function, where the increase from minimum to maximum or decrease from maximum to minimum occurs within one time step. We applied this form to the LAI and Rsc as shown in Fig. 5. Here the maximum of LAI is set to 6 $\mathrm{m^2\,m^{-2}}$, which is the observed maximum plus SD of the LAI2000 measurements. The minimum of Rsc is set to 40 $\mathrm{s\,m^{-1}}$. For this kind of approximation the start, and therefore the length of the growing season becomes important, because the maximum transpiration rate occurs immediately after leaf unfolding. In Fig. 5 we compare two different parameterisations for dynamical estimating leaf unfolding, i.e. the Max1 and the IPG235 parameter set (Table 1).

The NSCs for both simulations are 0.89 (Table 4), which is even a bit better than for applying the direct LAI measurements. However, PBIAS values are negative for the step function simulations, where they are positive for the simulations using LAI measurements. Negative PBIAS values indicate a stronger drying signal.

Differences in PAW are only visible in the period when parameterisation is different (Fig. 5). The year 2013 shows no drought event in spring, where effects would be more obvious. There are small differences in May, where the step function simulation using the Max1 parameters are closer to observations.

However, the abrupt increase to the maximum transpirations rate immediately after leaf unfolding is rather unrealistic as already shown by the LAI measurements. Unfolding of leaves in nature can happen very quickly, as everybody can observe when spring comes late in the year, followed by favourable growth conditions. When spring starts early the full leaf development can take much longer. To account for this and to further improve our model fit we changed the annual development of LAI and Rsc by using these parameters for manual model calibration, guided by the course of LAI measurements mainly. Major changes are higher LAI and lower Rsc values at the date of leaf unfolding, i.e. $2\,m^2\,m^{-2}$ and $150\,s\,m^{-1}$, respectively. The date of leaf unfolding is estimated with the dynamic approach like in the step function simulations. This resulted in modelled higher transpiration rates in spring. Besides the annual course of LAI and Rsc is described more detailed and more similar to the observed LAI dynamics – the LAI increase and decline is smoother but also starts a bit earlier in the year and last a bit longer in autumn. Due to that smoother increase in spring the sensitivity to deviations in estimating the date of leaf unfolding is reduced.

Due to these changes the NSC increased to 0.90 for both Max1 and IPG235 parameter sets. This is the best fit obtained in manual calibration procedure (Table 4). PBIAS values are positive for the adjusted models, which is a slightly too small drying signal. However, the magnitudes of PBAIS and RSR values are smaller than for the step function simulations, indicating better agreement with observations and lower root mean square errors or residual variations (Moriasi et al., 2007).

3.2.3 Long term simulations

In all simulations shown for the year 2013, the effects on PAW caused by changes in estimated leaf unfolding are quiet low, due to the high soil water contents in spring

2013. Therefore, we applied all simulations for the years 1969–2013, which was the longest period meteorological forcing data are available without missing data. A focus is set to the year 2012, which was characterized by an early drought event in May. Because of missing data there is no complete set of soil water content information available for this year and there is no information about LAI and Rsc for 2012 that can be used to parameterise the hydrological model. So no evaluation of model fit is possible for 2012 or the other years of the period 1969–2013, like it is done for 2013.

To illustrate the effects for the different courses of LAI and Rsc development as well as the estimation of leaf unfolding, Fig. 7 shows the precipitation, the plant available water and the GWR for the step function and for the adjusted simulations combined with the estimates of leaf unfolding, i.e. the Max1 and IPG235 parameter set, respectively. In 2012 and 2013 as well as for both estimations of leaf unfolding, the adjusted simulation shows the highest GWR and the step function simulations results in the lowest GWR. The reason for this the change in transpiration in spring, as described due to the different parameterisations of the step function and adjusted course for LAI and Rsc. However, the largest effects on GWR are caused by the different estimation of leaf unfolding date (Fig. 7). In the step function experiments GWR is zero in 2012 with both the Max1 and the IPG235 parameterisations of leaf unfolding. Plant available water is reduced stronger for the Max1 parameterisation, due to the early start of the growing season. However, this early leaf unfolding fits better to the observations in Reiffenhausen. For the adjusted simulations GWR is zero for the Max1 parameterisation only. GWR in May and July 2012 only occurs in the simulation using the adjusted courses for LAI and Rsc as well as for all simulations using the IPG235 parameterisation for leaf unfolding. For the year 2012 tensiometer measurements in 20, 60 and 120 cm soil depth are available. The measurements show a drought period in May 2012, where the tensiometers in 20 cm soil depth run out the measuring range, i.e. a matrix potential was lower than approx. −800 hPa. Starting from May 2012 the tensiometers in 60 and 120 cm soil depth indicated a consistent drying signal (not shown). Additionally the poplar SRC in 2012 is younger and therefore less water demanding than the poplar

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SRC parameterised in the model, applied for these analyses. This indicates that GWR after May 2012 is very unlikely in these simulations.

The parameterisation using the adjusted course for LAI and Rsc, based on the measured course of LAI, in combination with the Max1 parameterisation for leaf unfolding, calibrated at local observations, seems to be the most realistic model simulation (LAIadjusted Rsc40 Max1). By comparing all four model parameter combinations shown in Fig. 7, one can switch completely from GWR present in 2012 to absent.

Table 5 summarizes the evapotranspiration (ETR) and GWR for all simulations, averaged over all years for the period 1969–2013, as well as for the 5 driest and 5 wettest years of this period. GWR averaged over all years varies from 80 mm yr^{-1} to 145 mm depending on the approximation of the annual course of LAI and Rsc and the estimation of leaf unfolding. The ratio of maximum and minimum of the all year averages of GWR for the different simulations is approx. 1.8. This factor is approx. 3 for the 5 driest years and approx. 1.7 for the 5 wettest years, showing that especially the model results for dry years are sensitive to the parameterisations used.

4 Discussion

Not all necessary model parameters for WaSim could be measured in detail. One example is the implemented assumption on rooting depth which was measured in 2012, and was set to 1 m for modelling which is comparable to the commonly used values presented in Raissi et al. (2009).

Measuring Rsc in the field is rather challenging. For hydrological modelling we are interested in more theoretically minimum values, indicating optimal transpiration. These conditions are hardly found in reality. In addition the measurements are effected by soil water availability as well as rapidly changing atmospheric conditions. Breuer et al. (2003) summarises values for minimal stomatal resistance for various plants. Values for populus clones (*Populus grandidenata*, *Populus tremula* and *Populus tremuloides*) are ranging from 102 to 400 s m^{-1}. Our measured minimum of Rsc for poplar

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clone Max1 (*Populus nigra × Populus maximowiczii*) is lower: 80 s m^{-1}. Yet we needed to further reduce Rsc to 40 s m^{-1} for modelling in order to match the observed soil water contents. On the one hand the low observed minimum of 80 s m^{-1} shows that specific measurements of Rsc are helpful. On the other hand the measurements of Rsc were still too high to produce plausible results with WaSim.

The LAI measurements show a systematic difference between the two measurement devices, whereas the LI191SA seems to overestimate LAI taking the destructive method as a reference. In situ measurements of LAI are helpful to determine the maximum value, but differences due to the different estimation methods including underlying assumptions should be considered. The annual development of LAI is indispensable information to adjust and improve the model parameterisation of annual course. The measured LAI development represents local conditions and is therefore valid for the measurement site and time period only. Approximations of seasonal course are advisable to enable the transferability to other sites and years. A crucial factor here is the date of leaf unfolding, determining the start of LAI increase. For the determination of this date phenological stages have been defined. To describe the date of leaf unfolding various models are available, based on air temperature, soil temperature, photoperiod, day length or radiation. All models have to be calibrated for specific plants species. There is also evidence that local conditions like latitude or altitude of observations are influencing the calibration of the phenological model. Furthermore the derivation of parameters for the phenological model will depend on the observed data, e.g. the detection of extremely early or late leaf unfolding dates as well as the climate data, which has to be appropriate for the observed site. For poplar clone Max1 we could not find parameter sets in literature, so we used for comparison the IPG235 parameters of Menzel (1997) for *Populus tremula*, which is better investigated. The period of parameter adjustment used by Menzel (1997) is 1959–1993, and is based of several phenological stations, whereas our derived parameters are based on 2 years at one site. However, these two years shows a wide spread in the date leaf unfolding started. The parameters from Menzel (1997) should be generally more valid, because of the higher number of observations. Yet the use of IPG235 parameters resulted in an underestimation of observed variability, compared to the observations for *Populus tremula* in Tharandt. Differences between IPG235 and Max1 also show the importance of parameterisations for local site conditions and specific species. Comparing the parameter sets presented in Table 1 these effects become visible.

Especially threshold temperatures for chilling and forcing units, T_0 and T_1 vary more widely between IPG235 and Max1. Due to this wider range the model is able to describe extreme values and therefore a higher variability of the date of leaf unfolding, which was observed in our calibration years 2012 and 2013. We evaluated our parameter set on observations of the poplar SRC Reiffenhausen in 2014 and the poplar SRC Großfahner (2012–2014), which was planted with the same clone and in the same year like Reiffenhausen. The differences for the date of leaf unfolding between observations and the Max1 model setup are low and within the observed variability. The use of IPG235 parameters for the Max1 clone, which is a common procedure when specific values are missing, can result in large deviations as shown for GWR, especially in the year 2012 with the drought period in spring.

The source of temperature data also influences the parameters derived for phenological models as well as the results obtained by applying these parameter sets. We compared the estimated DOY of leaf unfolding derived with local temperature measurements and with temperatures of the nearest DWD stations. For Reiffenhausen, with the nearest DWD station Göttingen, we additionally tested an altitude correction using the vertical temperature gradient of $-0.0065\,^{\circ}\mathrm{C\,m^{-1}}$ to account for 158 m altitude difference between Göttingen (167 m a.s.l.) and Reiffenhausen (325 m a.s.l.). Deviations in DOY of leaf unfolding are small when using the DWD temperature instead of the local measurements. Interestingly, the altitude correction of temperature increases differences in DOY of leaf unfolding comparing to observations. The reason could be the often occurring inversion conditions, when the air temperature in Reiffenhausen is higher than in Göttingen, so that implemented altitude reduction of temperature increases the differences even more, due to that also the differences of the estimated DOY of leaf

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unfolding increase. The effects of the altitude correction are larger for the Max1 than for the IPG235 parameter set, because our model is more sensitive to extreme values due to higher T_0 and lower T_1 temperatures. This shows the importance of applying the local temperatures, associated to the phenological observations, to calibrate and use the temperature-dependent phenological models. The use of local temperatures improves the estimation of leaf unfolding and better represents inter annual variability.

According to the criteria of Moriasi et al. (2007) the hydrological model results using measured values of LAI and Rsc, where the start and development of leaf unfolding is implemented, are satisfactory only for the simulation LI191SA with Rsc = 80 $s\,m^{-1}$. The simulation using the LAI values from the LAI2000 fails to satisfy the recommended criteria (Table 4). However the model produces better agreement with observations when Rsc minima of 40 $s\,m^{-1}$ are used with any LAI data. The reduction of Rsc is a consistent way to simulate the observed soil water conditions. An increase of LAI could lead to lower soil water contents as well, but is also effecting soil evaporation and interception evaporation. Additionally larger values for LAI, necessary to minimize the model deviations to measurements, have to be unrealistically high for the poplar SRC investigated here. When using a Rsc minimum of 40 $s\,m^{-1}$ together with measured LAI the model evaluation is good for the year 2013, reaching NSC values of 0.87 and 0.89 for the LAI2000 and LI191SA simulations. Data of such intense measurement campaigns are not available for all sites were hydrological modelling should be done. Therefore literature values, often providing maximum or minimum values for LAI and Rsc only, are used and the annual course has to be modelled. The question of transferability of these values to different sites, years or even species has to be solved. The applied step function is the simplest approximation of the annual course for LAI and Rsc. These simulations also pass the recommended criteria for a satisfactory model performance (Table 4).

For the year 2013 the best model fit could be obtained by the adjusted annual courses for LAI and Rsc. They are based on the observed course and maximum values of LAI measurements.

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The weather regime and therefore the development of soil water conditions are not suitable in 2013 to show the effects of different estimates for the start of leaf unfolding in spring. Drought conditions started not until July 2013. Therefore we performed scenario simulation by transferring the vegetation parameterisation for 2013 to the weather regime of 2012. This year was characterized by a drought period in spring. In consequence the effects of different estimates of DOY of leaf unfolding are pronounced. The adjusted simulations using the IPG235 parameters to estimate leaf unfolding, i.e. later leaf unfolding by approx. 30 days in 2012 show GWR in this year. Due to the delayed start of the growing season the drought stress in spring is missed in the model mostly, leading to wetter soil conditions which benefits percolation and rewetting and finally enlarges GWR (Fig. 7). The tensiometer measurements available for 2012 suggest that GWR is rather unlikely for this year. The step function simulation using the IPG235 parameters for leaf unfolding and both adjusted simulations (Max1 and IPG235) result in zero GWR for the year 2012. However, the strongest simplification of the course of LAI and Rsc, i.e. the step function, shows the lowest GWR for 2013 and for the long term simulations (Table 5).

In Fig. 7 the effects of the different simulations on GWR are presented for the years 2012 and 2013, which are characterized by rather different weather regimes. Whereas a realistic description of LAI and Rsc seems to be less important in 2013, it is even more essential in 2012, showing the importance of distinct spatial and temporal characteristics for local modelling.

We performed a long term simulation, by keeping the parameterisation for the vegetation constant for the period 1969–2013 to account for the effects of climate variability. This is a more theoretical scenario, because it accounts for changes in climate forcing only. In reality also the vegetation characteristics are changing over the years, as well as soil properties on a longer time scale, especially for SRC, whereas rotation cultivation is applied, e.g. harvesting and resprouting. Particularly the rotation cultivation can reduce extreme drought conditions, when dry years coincide with rotation stages that have a lower water demand. The vegetation parameterised here can be seen as

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fully developed in hydrological terms, characterized by a large water demand. The simulations here are rather artificial, especially by succeeding dry years when soil water storage is not refilled completely in winter and drought conditions are influencing the following growing season. Nevertheless the effects caused by different descriptions of vegetation parameterisations are quiet large (Table 5). Especially on a local scale such differences can be important by evaluating effects of land use change, particularly in dry years.

Taking into account, that the best model evaluation for 2013 is achieved with the adjusted course of LAI and Rsc, the adjusted simulation using the Max1 phenology parameters seems to be the most reasonable parameterisation. It fits best to the evaluation in 2013.

5 Conclusions

For hydrological analysis of some area or sites with the focus on land use change or climate change the adequate parameterisation of the vegetation cover is important by determining processes like soil evaporation, interception evaporation and transpiration. Our study shows that LAI, Rsc as well as the beginning and length of growing season are the sensitive parameters when investigating the effects of an enhanced cultivation of SRC on local water budget, i.e. GWR, by means of the hydrological model WaSim. Most sensitive is the parameterisation of the beginning of the growing season. When this estimation is wrong, such as shown for the different species as in the IPG235 and Max1 parameterisation (Table 1), the accuracy of LAI and Rsc description plays a minor role.

The implementation of locally measured vegetation parameters for hydrological modelling has both advantages and drawbacks. Measurements are not always feasible, because they are time consuming and expensive or the vegetation is inaccessible. In such cases the use of some appropriate literature values or adjacent observations is the common practice. The present study displays for the parameter LAI, that the simulations using locally measured plant specific values show the suitability of data. However, for Rsc the benefit of direct use of local measurements is arguable: the minimal values had to be reduced within WaSim, to produce model results comparable with measurements. In consequence the implementation of Rsc values from literature for hydrological modelling without accompanying measurement data for model evaluation can produce very uncertain results. The analyses done here illustrate that the locally adjusted vegetation parameterisation shows the best model fit. Additionally the adjusted course of LAI and Rsc is less sensitive to different estimates for leaf unfolding, due to a slower increase in spring compared to a step functional annual course. But the adjusted courses are also approximations and not a distinct measure and are therefore more generally valid for different sites and years, than a direct use of measured parameters.

For the land use poplar SRC there are certain years where the modelled GWR is reduced to zero, like in the year 2012 (Fig. 7). Different parameterisations for vegetation characteristics are influencing modelled GWR for those years producing a wide range from GWR present or completely absent.

Hydrological models are often used to analyse effects of climate and land use changes on spatial and temporal scale becoming smaller and smaller. Approximations in the description of vegetation, a lack of local information (also soil and climate description), the transfer of inappropriate parameters and lacks in model formulation can cause large differences in simulation results. To account for small-scale and local effects of land use change more detailed descriptions of sites and processes are necessary to capture the spatial and temporal variability of effects. Especially when analysing extremes, they are often underestimated when the description of site and processes are insufficient.

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Table 1. Parameters of the modified approach for estimating leaf unfolding according to Cannell and Smith (1983), which is used in WaSim. Estimated day of years (DOY) of leaf unfolding for Reiffenhausen (2012, 2013) are used to calibrate the Max1 parameters T_0, T_1, a and b, i.e. threshold temperature for chilling units and forcing units and two tree specific regression parameters, respectively. Additionally the parameter set for IPG235 according to Menzel (1997) (Appendix A7) is shown.

Parameter	Max1	IPG235 (Menzel, 1997)
T_0 [°C]	10	8
T_1 [°C]	2	5
a	2200	1693.4161
b	−403	−301.9361

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Table 2. Observed and estimated day of years (DOY) of leaf unfolding for Reiffenhausen and Großfahner. The Max1 parameters are calibrated at the observations in Reiffenhausen using local temperatures (2012 and 2013) and evaluated with Reiffenhausen (2014) and Großfahner (2012–2014). Additionally the DOY of leaf unfolding is compared to estimates using the IPG235 parameter set as well as the temperatures of the nearest DWD climate station (Göttingen for Reiffenhausen, distance approx. 17 km; Dachwig for Großfahner, distance approx. 3.5 km) are presented.

	Observed	Max1	Max1	IPG235	IPG235
temperature data		local	nearest DWD	local	nearest DWD
Reiffenhausen DOY 2012	88	91	89	119	121
Reiffenhausen DOY 2013	115	112	112	125	126
Reiffenhausen DOY 2014	83	82	85	111	113
Großfahner DOY 2012	90	89	88	111	112
Großfahner DOY 2013	115	113	112	121	121
Großfahner DOY 2014	89	–	86	–	103

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Table 3. Description of the eight performed model simulations. All model parameters are constant, except leaf area index (LAI), stomatal resistance (Rsc) and the date of leaf unfolding for the two parameter sets Max1 and IPG235.

Version	LAI	Rsc	Leaf unfolding
LAI2000 Rsc80	LAI2000 measurements	minimum 80 $s\,m^{-1}$ (LAI > 1)	defined by measured LAI
LAI2000 Rsc40	LAI2000 measurements	minimum 40 $s\,m^{-1}$ (LAI > 1)	defined by measured LAI
LI191SA Rsc80	LI191SA measurements	minimum 80 $s\,m^{-1}$ (LAI > 1)	defined by measured LAI
LI191SA Rsc40	LI191SA measurements	minimum 40 $s\,m^{-1}$ (LAI > 1)	defined by measured LAI
LAIstep Rsc40 Max1	step function (6 in growing season; else 1)	minimum 40 $s\,m^{-1}$ (LAI > 1)	Max1 model
LAIstep Rsc40 IPG235	step function (6 in growing season; else 1)	minimum 40 $s\,m^{-1}$ (LAI > 1)	IPG235 model
LAIadjusted Rsc40adjusted Max1	course calibrated to improve model fit (max. = 6)	minimum 40 $s\,m^{-1}$ (LAI > 1)	Max1 model
LAIadjusted Rsc40adjusted IPG235	course calibrated to improve model fit (max. = 6)	minimum 40 $s\,m^{-1}$ (LAI > 1)	IPG235 model

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Table 4. Statistical parameters for model evaluation in terms of the accuracy of simulated data compared to measured values. Nash–Sutcliffe efficiency criterion (NSC), percent bias (PBIAS), and ratio of the root mean square error to the SD of measured data (RSR) are calculated from plant available soil water till 1 m soil depth as derived from model simulations and soil water content measurements for the period from April till December 2013, to cover the period of most variability.

	NSC	RSR	PBIAS [%]
Recommended as satisfactory by Moriasi et al. (2007)	> 0.5	≤ 0.7	±25
LAI2000 Rsc80	0.44	0.75	19.2
LAI2000 Rsc40	0.87	0.37	5.5
LI191SA Rsc80	0.69	0.56	13.9
LI191SA Rsc40	0.89	0.33	0.0
LAIstep Rsc40 Max1	0.89	0.33	−2.0
LAIstep Rsc40 IPG235	0.89	0.33	−1.7
LAIadjusted Rsc40adjusted Max1	0.90	0.31	1.3
LAIadjusted Rsc40adjusted IPG235	0.90	0.31	1.6

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Table 5. Precipitation ($mm\,yr^{-1}$), total evapotranspiration (ETR) and ground water recharge (GWR) for the period 1969–2013. Simulations are shown for the step-function simulation and the adjusted course for leaf area index and stomatal resistance, using the leaf unfolding according to the Max1 and IPG235 parameter set for simulating leaf unfolding. The parameterisation for poplar is equal to that derived for 2013 for the whole period, i.e. the same vegetation hydrological modelled driven by different weather conditions. Values are summed up for all years (1969–2013) of the period and for the 5 driest and 5 wettest years, respectively.

	ETR (all years)	ETR (5 driest)	ETR (5 wettest)	GWR (all years)	GWR (5 driest)	GWR (5 wettest)
precipitation	676.7	500.4	896.6	676.7	500.4	896.6
LAIstep Rsc40 Max1	527.8	487.1	533.6	79.7	23.2	140.2
LAIstep Rsc40 IPG235	488.5	463.0	482.6	105.0	37.9	170.4
LAIadjusted Rsc40adjusted Max1	484.1	460.8	477.9	107.1	41.3	173.9
LAIadjusted Rsc40adjusted IPG235	425.9	424.4	411.7	144.7	68.1	232.9

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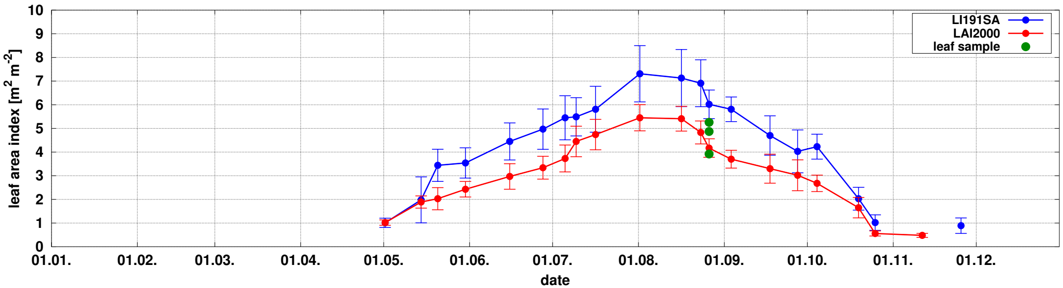

Figure 1. Means and SDs of leaf area index of the poplar SRC Reiffenhausen in 2013. Measurements of two optical devices: LI191SA calculated with constant extinction coefficient $k = 0.5$ and LAI2000 are shown. LAI values obtained by destructive harvesting at the 26 August on three plots are shown as green dots.

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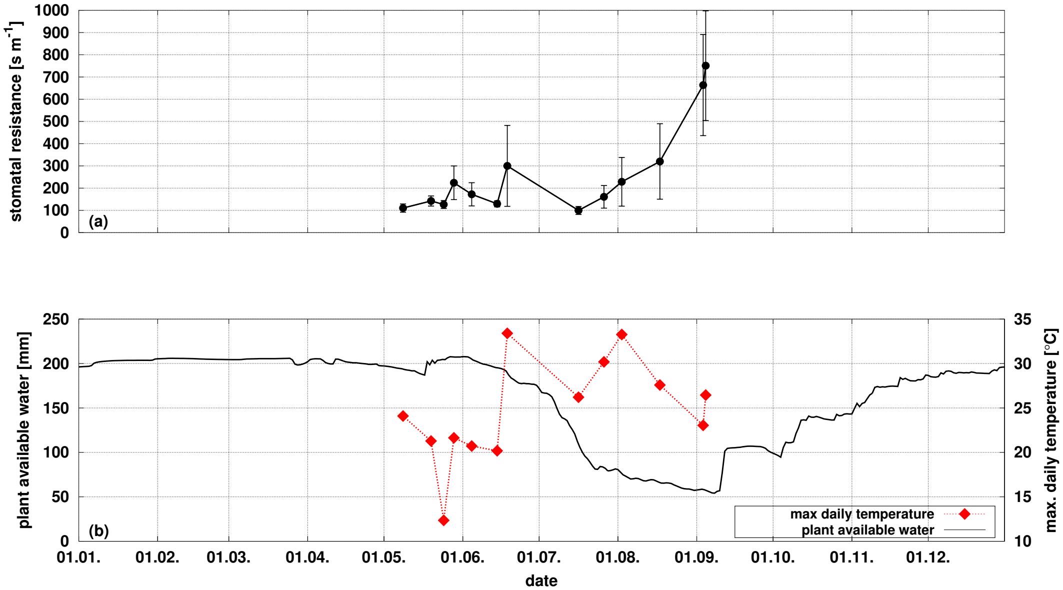

Figure 2. Means and SDs of stomatal resistance of sun leaves derived from 10 to 11 repetitions every day at 10 measurement plots and **(a)** the plant available water, calculated from soil water content measurements until 1 m soil depth and **(b)** daily maximum temperature at the poplar SRC Reiffenhausen in 2013. High temperatures effecting stomatal resistance (18 June); starting from August drought stress occurred, increasing the stomatal resistances.

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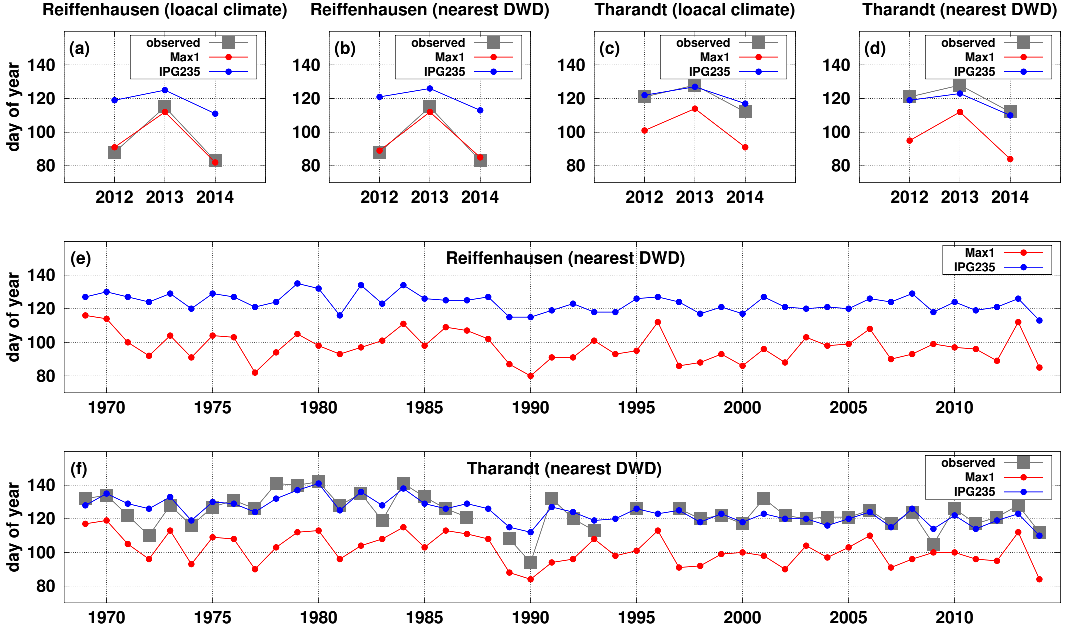

Figure 3. Estimated day of year of leaf unfolding using the Max1 and IPG235 parameters for the site Reiffenhausen with local temperature measurements **(a)** and temperatures from the nearest DWD station Göttingen **(b)** for the years 2012 to 2014; same for Tharandt, local temperatures **(c)** and nearest climate station Wildacker **(d)**; with observations. The lower subplots show long term estimates for the day of year of leaf unfolding using the DWD temperatures for Reiffenhausen **(e)** and for Tharandt **(f)**, where also long term observations are available.

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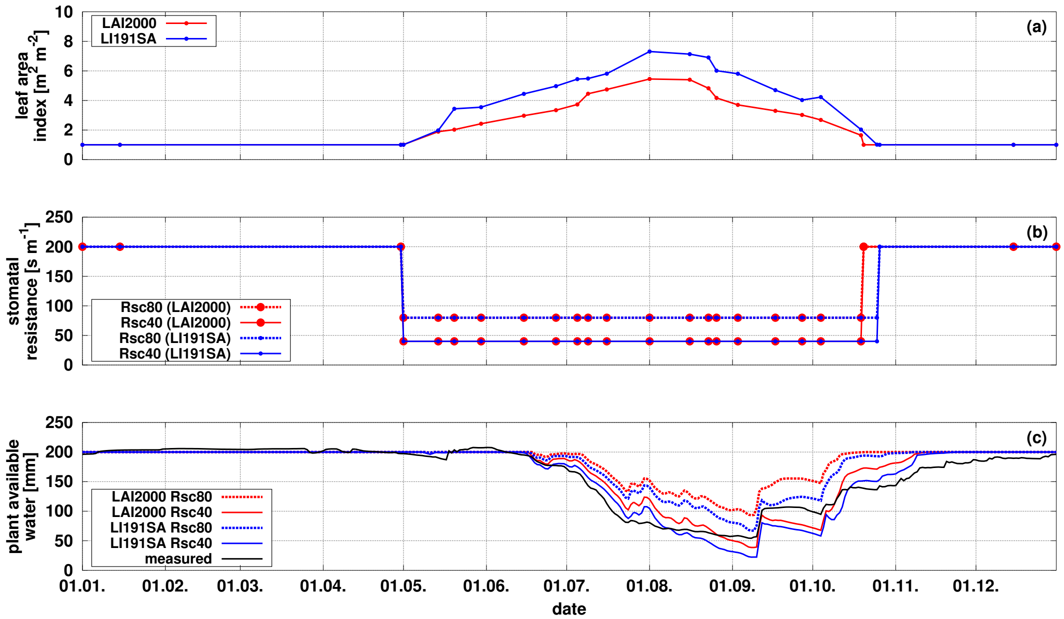

Figure 4. Leaf area index **(a)** and stomatal resistance **(b)** as parameterised from measurements. Leaf area index is used as measured, LAI2000 (red) and LI191SA (blue). Stomatal resistance is set to the measured minimum, i.e. $80\,\mathrm{s\,m^{-1}}$ (dashed line) and to $40\,\mathrm{s\,m^{-1}}$ (solid line) as leaf area index is larger than 1. Length of growing season is determined by the leaf area observations. Simulation results using the four combinations of leaf area index and stomatal resistance are shown as plant available soil water, calculated until 1 m soil depth and compared to values based on soil water content measurements **(c)**.

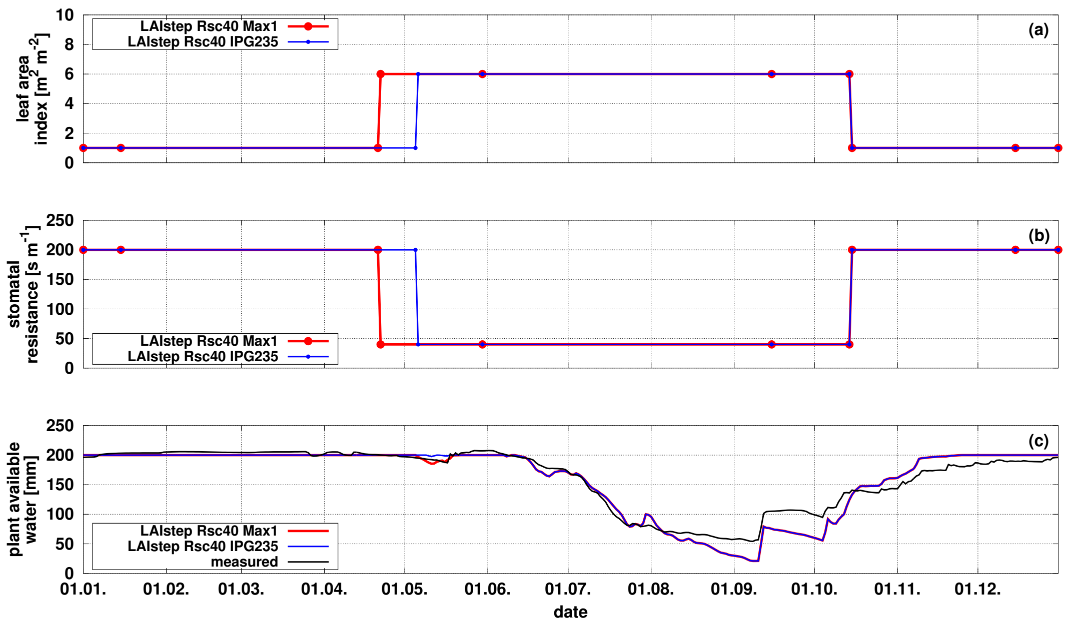

Figure 5. Leaf area index (LAI) **(a)** and stomatal resistance **(b)** parameterised as step function, using maximum and minimum values in the growing season 2013, respectively. LAI is set to 6, stomatal resistance is set to $40\,\mathrm{s\,m^{-1}}$ when LAI is larger than 1. Leaf unfolding is determined by the dynamic phenology approach implemented in WaSim, using the Max1 parameterisation and IPG235. Simulations results using the two combinations of LAI and stomatal resistance are shown as plant available soil water, calculated till 1 m soil depth and compared to values based on soil water content measurements **(c)**.

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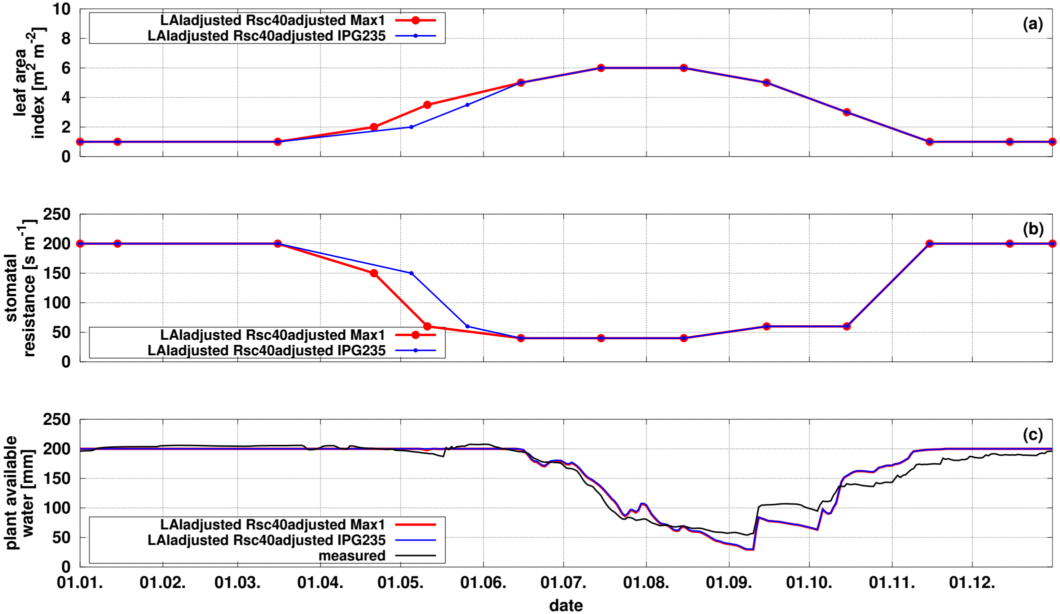

Figure 6. Leaf area index **(a)** and stomatal resistance **(b)** as parameterised from adjusted values for 2013. Maximum of leaf area index is set to 6, minimum of stomatal resistance is set to $40\,\mathrm{s\,m^{-1}}$. Leaf unfolding is determined by the dynamic phenology approach implemented in WaSim, using the Max1 and IPG235 parameterisation. The annual course of leaf area index and stomatal resistance is orientated on measurements for leaf area and used as calibration parameter for stomatal resistance. Simulations results using the two combinations of leaf area index and stomatal resistance are shown as plant available soil water, calculated till 1 m soil depth and compared to values based on soil water content measurements **(c)**.

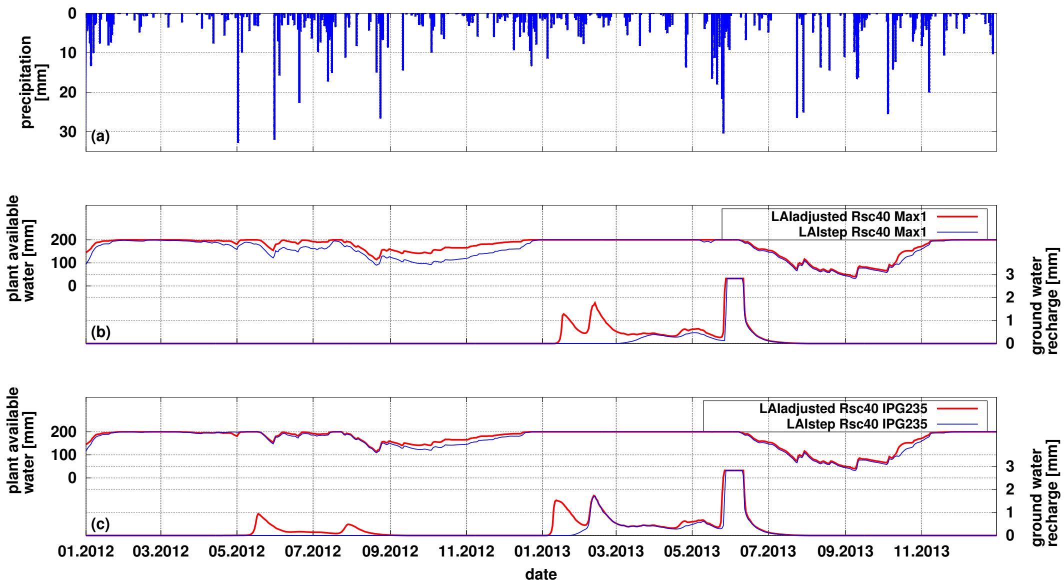

Figure 7. Measured daily precipitation **(a)**. Plant available water and ground water recharge as simulated for the step-function and adjusted course for leaf area index and stomatal resistance, using the leaf unfolding parameters Max1 **(b)** and IPG235 **(c)** for simulating leaf unfolding. The parameterisation for poplar is equal for 2012 and 2013, i.e. the same vegetation hydrological modelled driven by different weather conditions, i.e. a drier year 2012 with an earlier dry period in May.

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