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# Evaluation of root water uptake in the ISBA-A-gs land surface model using agricultural yield statistics over France

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### Abstract

The interannual variability of cereal grain yield and permanent grassland dry matter yield is simulated over French sites by the Interactions between Soil, Biosphere and Atmosphere,  $CO_2$ -reactive (ISBA-A-gs) generic Land Surface Model (LSM). The two soil profile schemes available in the model are used to simulate the above-ground biomass ( $B_{ag}$ ) of cereals and grasslands: a 2-layer force-restore (FR-2L) bulk reservoir model and a multi-layer diffusion (DIF) model. The DIF model is implemented with or without deep soil layers below the root-zone. The evaluation of the various root water

- uptake models is achieved by using the French agricultural statistics of Agreste over the 1994–2010 period at 45 cropland and 48 grassland sites, for a range of rooting depths. The number of sites where the simulated annual maximum  $B_{ag}$  presents a significant correlation with the yield observations is used as a metric to benchmark the root water uptake models. Significant correlations (*p* value < 0.01) are found for up to 29% of the cereal sites and 77% of the grassland sites. It is found that modelling additional subroot
- <sup>15</sup> zone base flow soil layers does not improve (and may even degrade) the representation of the interannual variability of the vegetation above-ground biomass. These results are particularly robust for grasslands as calibrated simulations are able to represent the extreme 2003 and 2007 years corresponding to unfavourable and favourable fodder production, respectively.

#### 20 1 Introduction

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Modelling the land surface processes and the surface energy, water and carbon fluxes is an important field of research in the climate community, as soil moisture and vegetation play an essential role in the climatic earth system (Seneviratne et al., 2010). A regular improvement and assessment of generic Land Surface Models (LSMs) is also required. In particular, the seasonal and interannual variability of the vegetation interacts with hydrological processes and must be represented well (Szczypta et al.,



2012). Modern LSMs such as Interactions between Soil, Biosphere and Atmosphere,  $CO_2$ -reactive (ISBA-A-gs) (Calvet et al., 1998; Gibelin et al., 2006) or ORganizing Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE) (Krinner et al., 2005) are able to simulate the diurnal cycle of water and carbon fluxes and, on a daily basis, plant

- <sup>5</sup> growth and key vegetation variables such as the above-ground biomass ( $B_{ag}$ ) and the Leaf Area Index (LAI). In areas affected by droughts, soil moisture has a marked impact on plant growth, and the way root water uptake is represented in such LSMs may influence the simulated  $B_{ag}$  and LAI values, in particular the maximum values reached every year. Therefore, long time series of observations related to the latter quantities,
- <sup>10</sup> such as agricultural yields, have potential in the evaluation of the simulation of the Available soil Water Content (AWC) and of root water uptake in LSMs provided their interannual variability is governed by climate and not by trends or changes in agricultural practices.
- In Europe, a marked positive trend in crops yields has been observed in the last 45 years, due to the agricultural intensification and to the evolution of farmer's practices (Smith et al., 2010a, b). However, Brisson et al. (2010) and Gate et al. (2010) have shown that yields have been stagnating in Europe since the beginning of the 1990s, and particularly since 1996 in France. Therefore, it can be assumed that in the last two decades the year-to-year change in the large scale yield of a given rainfed crop type is
- <sup>20</sup> mainly driven by the climate variability. In Europe, Smith et al. (2010a, b) showed that the agricultural statistics can be used to assess crop simulations at the country level. At a finer spatial scale over France, Calvet et al. (2012), hereafter referred to as Ca12, have used agricultural statistics (Agreste, 2014) to benchmark several configurations of the ISBA-A-gs LSM through the correlation between yield time series and B<sub>ag</sub> simula-
- tions for the 1994–2008 period. Even if the Ca12 simulations used a simple, single-layer representation of the root-zone soil moisture and did not take into account the agricultural practices, a good representation of the interannual variability of the biomass production was achieved over many sites in France. By performing a sensitivity study on different parameters of the model, they concluded that the Maximum Available soil



Water Content (MaxAWC) and the mesophyll conductance in well-watered conditions  $(g_m)$  were the two keys parameters driving the interannual variability of the simulated  $B_{ag}$ . In particular, they showed that the model was markedly sensitive to MaxAWC (especially at low MaxAWC values).

- <sup>5</sup> In this study, the method proposed by Ca12 is used to evaluate a new option of the ISBA-A-gs model using a multilayer soil model permitting the detailed representation of soil moisture and soil temperature profiles. Several root water uptake models are compared.
- The various versions of ISBA-A-gs are presented in Sect. 2, together with the annual yield statistics of Agreste. The results obtained with the different set of simulations are shown in Sect. 3 and the differences in the interannual variability of the various simulations of  $B_{\rm ag}$  are presented, together with the hydrological variables. The results are analyzed and discussed in Sect. 4 and the conclusions of this study are summed up in Sect. 5.

#### 15 2 Data and methods

# 2.1 Agricultural statistics in France

Agreste is an annually updated set of agricultural data over France (Agreste, 2014). An inventory of the land use in agriculture, and of the crop, forage and livestock production is made on a yearly basis. The data are provided for administrative units (hereafter referred to as "départements"). For crops and grasslands, annual grain yields and dry matter yields (GY and DMY, respectively) are supplied. A new version of Agreste with recalculation since 1989 has been recently published. In this study, the new Agreste dataset is used, over the 1994–2010 period, to examine the interannual variability of 45 winter/spring cereal crop sites and of 48 natural grassland sites (Fig. 1). For cere-

<sup>25</sup> als, we consider the six following crops: winter wheat, rye, winter barley, spring barley, oat and triticale. For grasslands, the DMY values of permanent grasslands are used.



They correspond to natural grasslands or grasslands planted at least 6 years before. Figure 2 shows the interannual variability of the average GY and DMY time series derived from Agreste over the considered sites. Over the 1994–2010 period, no significant (p value < 0.01) trend is observed for any of the time series. A few anomalous years

- affected by particular climate events can be noticed. For example, Fig. 2 shows that the severe summer drought of 2003 impacted both crop and grassland yields. In 2007, the grassland production was the highest of the whole period. Conversely, it was one of the worst in terms of crop yield. The 2007 year was marked by a warm spring (favourable to permanent grasslands), followed by a slightly cold summer (detrimental to cereals).
- <sup>10</sup> Furthermore, the rains were abundant over regions where the grassland sites of this study are located, and have also contributed to the higher production (Agreste Bilans, 2007; Agreste Conjoncture, 2007; Agreste Infos Rapides, 2007).

### 2.2 The ISBA-A-gs land surface model

The Interactions between Soil, Biosphere, and Atmosphere (ISBA) model (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996) was designed to describe the daily course of land surface state variables into global and regional climate models, weather forecast models, and hydrological models. In the original version of ISBA, a single root-zone soil layer is considered. A thin top soil layer is represented using the Deardorff (1977, 1978) force-restore approach. Soil characteristics such as soil-water and heat coefficients, the wilting point and the field capacity, depend on soil texture (sand and clay fractions). The stomatal conductance calculation is based on the Jarvis (1976) approach, and accounts for Photosynthetically Active Radiation (PAR), soil water stress, vapour pressure deficit and air temperature.

The representation of the soil physics of the initial version of ISBA was gradually <sup>25</sup> upgraded. A multilayer soil model including soil freezing processes was developed by Boone et al. (2000) and Decharme et al. (2011). The multilayer soil model explicitly solves the one-dimensional Fourier law and the mixed-form of the Richards equation. The multilayer representation is used to discretize the total soil profile. In each layer,



the temperature and the moisture are computed according to the hydrologic and texture layer characteristics. The heat and water transfers are decoupled: heat transfer is solely along the thermal gradient, while water transfer is induced by gradients in total hydraulic potential. Hereafter, the two-layer force restore model and the diffusion model are referred to as "FR-2L" and "DIF", respectively.

In addition to the simple Jarvis parameterization of stomatal conductance, Calvet et al. (1998) and Gibelin et al. (2006) have developed ISBA-A-gs. ISBA-A-gs ("A" stands for net assimilation of  $CO_2$  and "gs" for stomatal conductance) is a  $CO_2$  responsive version of ISBA able to simulate photosynthesis and its coupling to stomatal conductance. This option was used in studies on the impact of climate change (Calvet et al., 2008; Queguiner et al., 2011) and on the impact of drought on the vegetation in the Mediterranean basin (Szczypta, 2012).

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Under well watered conditions, the A-gs formulation is based on the model proposed by Jacobs et al. (1996) (Calvet et al., 1998, 2004; Gibelin et al., 2006). In this approach, the main parameter driving photosynthesis is  $g_m$ . Two distinct plant responses to drought are represented. For moderate soil water stress, the droughtavoiding (drought-tolerant) response results in the increase (decrease or no change) of the Water Use Efficiency (WUE). In the drought-tolerant response, WUE does not change or decreases. Moreover, distinct representations of the response to drought are used for herbaceous vegetation (Calvet, 2000) and forests (Calvet et al., 2004).

ISBA-A-gs contains a photosynthesis-driven plant growth model able to simulate LAI and the vegetation biomass on a daily basis. For herbaceous vegetation, the model simulates the above-ground biomass. The  $B_{ag}$  variable has two components (active biomass and structural biomass) related by a nitrogen dilution parameterization (Calvet

<sup>25</sup> and Soussana, 2001). The leaf nitrogen concentration  $N_{\rm L}$  is a parameter of the model affecting the Specific Leaf Area (SLA), the ratio of LAI to leaf biomass (in m<sup>2</sup> kg<sup>-1</sup>). The SLA depends on  $N_{\rm L}$  and on plasticity parameters (Gibelin et al., 2006). This version of ISBA-A-gs, called "NIT", is used in this study.



An assessment of the quality of ISBA-A-gs outputs variables has been performed in previous local studies with in-situ data over France (Rivalland et al., 2005; de Rosnay et al., 2006; Sabater et al., 2007; Brut et al., 2009; Lafont et al., 2012). Gibelin et al. (2006) have shown that the LAI simulated by ISBA-A-gs at a global scale is consistent with satellite-derived LAI products.

Furthermore, a radiative transfer model within the vegetation canopy describes the attenuation of the PAR through a self-shading approach and photosynthesis is calculated at three levels of the canopy using a three-point Gauss quadrature method (Jacobs, 1994). A New Radiative Transfer (hereafter referred to as "NRT") scheme was recently implemented in ISBA-A-gs by Carrer et al. (2013). The NRT is more detailed than the original model and a vertical profile of ten layers within the canopy is represented. Because of the heterogeneity of the different vegetation canopies, distinct bottom and top canopy layer parameterizations are considered. Also, NRT has distinct representations of sunlit and shaded leaves, with two PAR calculations at each layer. Carrer et al. (2013) showed that NBT represents better the Gross Primary Production

<sup>15</sup> Carrer et al. (2013) showed that NRT represents better the Gross Primary Production (GPP) at both local and global scales.

# 2.3 Root density and the soil water stress

In the DIF simulations, the root density profile (Y) is expressed by the following equation derived from Jackson et al. (1996):

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$$Y(d_{\rm L}) = \frac{1 - R_{\rm e}^{100 \times d_{\rm L}}}{1 - R_{\rm e}^{100 \times d_{\rm R}}}$$

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where  $Y(d_L)$  is the cumulative root fraction (a proportion between 0 and 1) from the soil surface to the bottom of a soil layer within the root-zone, at a depth  $d_L$  (m),  $d_R$  is the root-zone depth (m) and  $R_e$  the root extinction coefficient equal to 0.961 and 0.943 for crops and for temperate grasslands, respectively (Jackson et al., 1996). For a given value of  $d_R$ , the lower value of  $R_e$  for temperate grasslands corresponds to a cumulative

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(1)

root fraction higher than for crops close to the top soil layer, 15 % higher at  $d_{\rm L} = 0.36$  m, more than 40 % higher at  $d_{\rm L} < 0.05$  m. The cumulative root density is equal to 1 at the bottom of the root-zone soil layer ( $d_{\rm R}$ ).

The Soil Wetness Index of a top soil layer of thickness  $d_{\rm L}$  and of a soil layer at depth  $_{\rm 5}$   $d_{\rm L}$  (SWI<sub>top</sub> and SWI, respectively) are defined as:

$$SWI_{top}(d_L) = (w_{top}(d_L) - w_{top, wilt}) / (w_{fc, top} - w_{wilt, top})$$
(2)

$$SWI(d_L) = (w(d_L) - w_{wilt}(d_L)) / (w_{fc}(d_L) - w_{wilt}(d_L))$$
(3)

where  $w_{top}(d_L)$  and  $w(d_L)$  are the volumetric water content (in m<sup>3</sup> m<sup>-3</sup>) of a top soil layer of thickness  $d_L$  and at depth  $d_L$ , respectively, and the subscript "fc" and "wilt" indicate soil moisture at field capacity and at wilting point, respectively. In this study, the same soil type is used for all the simulations, and an homogeneous soil profile is assumed with sand and clay fractions of 32.0 and 22.8%, respectively, and  $w_{fc} = w_{top, fc} = 0.30 \text{ m}^3 \text{ m}^{-3}$  and  $w_{wilt} = w_{top, wilt} = 0.17 \text{ m}^3 \text{ m}^{-3}$ . Since the agricultural statistics we use concern large administrative units, it would have been illusory to try and use local soil texture properties.

The value of MaxAWC is expressed in units of kg m<sup>-2</sup> and depends on soil and plant characteristics: soil moisture at field capacity, soil moisture at wilting point ( $w_{fc}$  and  $w_{wilt}$ , respectively, in m<sup>3</sup> m<sup>-3</sup>) and rooting depth ( $d_{B}$ , in m):

<sup>20</sup> MaxAWC =  $\rho(w_{fc} - w_{wilt})d_{R}$ 

where  $\rho = 1000 \text{ kg m}^{-3}$  is the water density. The  $w_{\text{fc}}$  and  $w_{\text{wilt}}$  values are common to all the simulations and the different MaxAWC values are obtained by varying the root-zone depth ( $d_{\text{R}}$ ).

In the ISBA-A-gs simulations, a stress function  $F_2$  (dimensionless) is used to calculate photosynthesis and the plant transpiration flux ( $F_T$ , in kg m<sup>-2</sup> s<sup>-1</sup>). The  $F_2$  function varies between 0 (at wilting point or below) and 1 (at field capacity or above). Between these two limits,  $F_2 = SWI_{top}(d_R)$  in FR-2L and plant transpiration is driven by the total



(4)

soil water column in the root-zone. In the case of DIF simulations,  $F_2$  is the sum of the stress functions of each soil layer in the root-zone, i.e. SWI( $d_{Li}$ ), balanced by the root fraction  $R_d$  at depth  $d_{Li}$ :

$$F_2 = \frac{\sum_{i=1}^{N} [SWI(d_{Li}) \times R_d(d_{Li})]}{\sum_{i=1}^{N} R_d(d_{Li})}$$

<sup>5</sup> where *N* is the number of soil layers in the root-zone. The root water uptake in layer *i*,  $S_T(i)$  (in kg m<sup>-2</sup> s<sup>-1</sup>), is calculated as:

 $S_{\mathrm{T}}(i) = F_{\mathrm{T}} \times \mathrm{SWI}(d_{\mathrm{L}i})/F_{2}.$ 

2.4 Design of the simulations

In this study, the ISBA-A-gs LSM is used within version 7.2 of the SURFEX ("SURFace

EXternalisée") Earth surface modelling platform of Météo-France (Masson et al., 2013). For the first time, the NIT biomass option of the model and the NRT light absorption scheme are used together with the DIF multilayer soil configuration. Two representations of the soil hydrology (FR-2L and DIF options) are considered, for both C3 crops and grasslands. The model simulations are offline (not coupled with the atmosphere)
 and driven by a meteorological reanalysis. We consider that the vegetation cover fraction is equal to 1 across seasons. We use the ISBA-A-gs default avoiding (tolerant) response to the drought for C3 crops (grasslands). Standard values of the model pa-

rameters used in this study are summarized in Table 1. Six experiments are performed:

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- FR-2L, is based on the force-restore representation of the soil hydrology and is similar to the model configuration used by Ca12. The root-zone corresponds to the whole soil layer.
  - DIF1 uses the new DIF capability of SURFEX v7.2 (Fig. 3). As in FR-2L, the rootzone corresponds to the whole soil layer. The root-profile reaches the bottom of the soil layer and the total soil depth corresponds to  $d_{\rm R}$ .

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(5)

(6)

- DIF2 includes additional subroot zone base flow soil layers with respect to DIF1 and the deep soil layers contribute to plant transpiration through capillarity rises. It is assumed that MaxAWC is governed by the limited capacity of the plants to develop a root system in a deep soil and the number of subroot zone layers decreases when the rooting depth increases. A constant total soil depth of 1.96 m is prescribed and  $d_{\rm R}$  is varied between 0.36 and 1.76 m (Fig. 4).
- DIF3 is similar to DIF1, as soil depth is the main limitation of root water extraction. However, two additional base flow soil layers contribute to transpiration through capillarity rises. The total soil depth and  $d_{\rm R}$  are varied simultaneously, and two adjacent 0.1 m thick deep soil layers are represented (Fig. 5).
- DIF1-NRT permits assessing the impact of a refined representation of the  $CO_2$  uptake by the vegetation on the  $B_{ag}$  interannual variability, as the NRT light absorption option is used together with DIF1.
- DIF1-Uniform permits assessing the sensitivity of the ISBA-A-gs simulations to the shape of the root density profile. It corresponds to DIF1 simulations using a uniform root density profile instead of Eq. (1). These simulations are made over the 61-Orne département (see Sect. 4.1).

# 2.5 Atmospheric forcing

The atmospheric forcing data required for our simulations are provided by the SAFRAN
 ("Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige") mesoscale atmospheric analysis system (Durand et al., 1993, 1999). Precipitation, air temperature, air humidity, wind speed, incoming solar radiation and incoming infrared radiation are provided over France at 8km × 8km spatial resolution on a hourly basis. The SAFRAN product was evaluated by Quintana-Seguí et al. (2008) using independent in situ observations. One-dimensional model simulations are performed at the 8km × 8km spatial resolution of SAFRAN, at grid cells corresponding to cereal and



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natural grassland sites (Fig. 1). These grid cells correspond to plots located within a département and with at least 45% of their surface covered by either grasslands or crops, according to the average plant functional type coverage given by the 1 km × 1 km ECOCLIMAP-II global data base (Faroux et al., 2013).

#### 5 2.6 Optimisation of two key parameters

In this study, the method proposed by Ca12 is used: the values of two key parameters of the ISBA-A-gs simulations, MaxAWC and  $g_m$ , are explored and the parameter pair providing the best correlation coefficient (*r*) of the maximum annual value of  $B_{ag}$ ( $B_{ag_x}$ ) and GY (DMY) is selected, for C3 crops (grasslands). For the FR-2L experiment, the optimisation of both MaxAWC and  $g_m$  is performed for all the sites of Fig. 1. For the DIF1, DIF2, and DIF3 experiments, only MaxAWC is optimised and the  $g_m$  values derived from the FR-2L optimisation are used. In the case of crops,  $B_{ag}$  values after 31 July are not considered, to be consistent with the theoretical averaged harvest dates in France. Attempts were made to use other dates in July (not shown), without affecting the results of the analysis. On the other hand, new optimal  $g_m$  values are obtained together with MaxAWC for the DIF1-NRT experiment, as the representation of

photosynthesis at the canopy level differs from the other experiments. Moreover, major differences with Ca12 are that (1) a longer period is considered (1994–2010 instead of 1994–2008 in Ca12); (2) a more detailed screening of MaxAWC values is performed (12 values are considered, against 8 values in Ca12).

For all the experiments, MaxAWC ranges between 50 and 225 mm, with a lower increment between the small values (50, 62.5, 75, 87.5, 100, 112.5, 125, 137.5, 150, 175, 200 and 225 mm, 12 in total).

For the  $g_{\rm m}$  parameter, the same range of values as in Ca12 is used (from 0.50 to 1.75 mm s<sup>-1</sup>, 6 in total). For the three simulations DIF1, DIF2 and DIF3, the same values of optimal  $g_{\rm m}$  obtained for each site and vegetation type with the FR-2L version are used.



### 2.7 Metrics used to quantify the interannual variability

In Sect. 4, the following metrics are used: the Annual Coefficient of Variation (ACV), computed as the ratio of the standard deviation ( $\sigma$ ) of the simulated  $B_{ag_x}$  to the long term mean  $B_{ag_x}$ ,

$$5 \quad \text{ACV} = \sigma(B_{\text{ag}_{X}}) / \overline{B_{\text{ag}_{X}}}$$

the scaled anomaly  $(A_{\rm S})$  of  $B_{\rm ag_v}$  of a given year (yr):

$$A_{\mathrm{S},B_{\mathrm{ag}_{\mathrm{X}}}}(\mathrm{yr}) = \frac{B_{\mathrm{ag}_{\mathrm{X}}}(\mathrm{yr}) - \overline{B\mathrm{ag}_{\mathrm{X}}}}{\sigma(B\mathrm{ag}_{\mathrm{X}})}.$$

This metric is also called z score and can be applied to the Agreste cereal GY:

$$A_{S,GY}(yr) = \frac{GY(yr) - \overline{GY}}{\sigma(GY)}$$

<sup>10</sup> and to the Agreste grassland DMY:

$$A_{S,DMY}(yr) = \frac{DMY(yr) - \overline{DMY}}{\sigma(DMY)}.$$

#### 3 Results

3.1 Interannual variability of B<sub>agx</sub> values

#### 3.1.1 DIF1 vs. FR-2L

<sup>15</sup> Figures 6 and 7 show an example of the interannual variability of the simulated  $B_{ag}$  and AWC (in kg m<sup>-2</sup>) as simulated by FR-2L and DIF1 for C3 crops and grasslands of the 5432

(7)

(8)

(9)

(10)

61-Orne département. The optimal parameter values for C3 crops and grasslands are 1.75 and 0.5 mm s<sup>-1</sup> for  $g_m$ , and 200 and 50 mm for MaxAWC, respectively.

For C3 crops (Fig. 6),  $B_{ag_x}$  values for FR-2L tend to reach slightly higher values than for DIF1. The largest difference is observed in 1996. Furthermore, some differences

- occur in the senescence period, especially in 2001 and 2009. Conversely, the simulated AWC values are higher for DIF1, especially in winter. For both simulations, the wintertime AWC is often higher than MaxAWC (set to 200 mm), in relation to water accumulation above field capacity, in wet conditions. This phenomenon is more pronounced for DIF1 than for FR-2L. A crop regrowth is simulated by both FR-2L and DIF1 during years with a marked summer drought, in 1995, 1996, 1998, 2006 and 2010. During water water accumulation approximate provide the two summaries are accumulated by both FR-2L.
- 2010. During wet years (i.e. in 1994, 2000 and 2007), the two experiments provide similar AWC values at summertime.

For grasslands (Fig. 7), the two  $B_{ag}$  simulations are also very close. However, contrary to C3 crops, the  $B_{ag}$  values of the FR-2L simulation tend to be slightly lower than <sup>15</sup> the DIF1 ones (e.g. in 1997, 2002, 2007, and 2009). The other difference with C3 crops is the systematic occurrence of regrowths.

# 3.1.2 ISBA-A-gs simulations vs. Agreste observations

The départements where FR-2L  $B_{ag_x}$  simulations present significant (*p* value < 0.01) correlations with the Agreste GY and DMY time series are presented in Fig. 8, and the retrieved  $g_m$  and MaxAWC median values are presented in Table 2 for all the experiments, together with the number of départements presenting significant correlations with Agreste, for C3 crops and grasslands. With FR-2L, 12 (5) sites present significant positive correlations at the 1 % (0.1 %) level for C3 crops. For grasslands, 34 (22) sites present significant positive correlations at the 1 % (0.1 %) level for C3 crops. Although the considered period is longer than in Ca12 (17 yr instead of 15 yr), these results are similar to

<sup>25</sup> ered period is longer than in Ca12 (17 yr instead of 15 yr), these results are similar to those presented in Ca12, even if slight differences can be noticed, such as the number of sites with a significant correlation. In DIF simulations for C3 crops, DIF1 and DIF3 perform nearly as well as FR-2L, and they outperform DIF2: 10 (3) sites present



significant positive correlations at the 1 % (0.1 %) level for both DIF1 and DIF3, against 6 (2) for DIF2. For the grasslands, a larger proportion of sites (among 48) presents significant correlations, from 27 (10) sites for DIF2 to 36 (20) for DIF1. The addition of deep soil layers below the root zone tends to degrade the results, especially in DIF2. Finally, the DIF1-NRT simulations perform as well as FR-2L or better with 13 (4) and 37 (19) sites presenting significant positive correlations at the 1 % (0.1 %) level for C3 crops and grasslands, respectively.

#### 3.2 Impact of subroot zone soil layers

# 3.2.1 Optimal MaxAWC values

Table 2 shows that for C3 crops, the median MaxAWC value is higher for FR-2L than for DIF1 (125.0 and 112.5 mm, respectively). For DIF2 and DIF3, the median MaxAWC is even lower (81.3 and 93.8 mm, respectively). For grasslands, the median MaxAWC is less variable from one experiment to another (from 68.8 to 81.3 mm). In Table 2, the median MaxAWC values are calculated irrespective of which Agreste cereal GY values are used to derive MaxAWC. Among the 10 sites with DIF1 simulations presenting significant correlations at the 1 % level with Agreste, 8 sites share the same cereal Agreste yields with FR-2L.

These 8 sites are listed in Table 3 together with squared correlation coefficient ( $R^2$ ) values and MaxAWC for FR-2L and DIF1. The FR-2L  $R^2$  is higher than the DIF1  $R^2$ , except for 08-Ardennes and 63-Puy-de-Dôme. Again, the median MaxAWC is higher for FR-2L than for DIF1 (118.8 and 112.5 mm, respectively). The FR-2L MaxAWC value is lower than the DIF1 MaxAWC value only once, for the 61-Orne département. This indicates that the DIF1 root density profile tends to increase the impact of drought on plant growth for this site. Also, the largest difference in  $R^2$  between FR-2L and DIF1 is observed for this site.



#### 3.2.2 Plant growth

Table 2 shows that in DIF2 simulations the number of sites with a significant correlation at the 1 % level is lower than in other experiments. The use of DIF2 has a detrimental impact on the representation of the interannual variability by the plant growth model.

- <sup>5</sup> Figure 9 shows the impact of the root water uptake model on the simulated C3 crop  $B_{ag}$  and root-zone soil moisture for the 08-Ardennes département during the growing season, from April to July 1996. In the FR-2L, DIF1, DIF2, and DIF3 simulations shown in Fig. 9, the same  $g_m = 0.5 \text{ mm s}^{-1}$  and MaxAWC = 75 mm values are used. The growth period is longer in the DIF2 simulation than in the other ones, with senescence starting
- <sup>10</sup> only during the second half of July. At the same time, the DIF2 root-zone soil moisture presents the highest values. It appears that in the DIF2 simulation, the additional water supplied by capillarity rises from the subroot zone soil layers has a marked impact on the phenology, with the date of maximum  $B_{\rm ag}$  shifted to the end of July and a much higher  $B_{\rm agx}$  value than in the other experiments (1.02 kg m<sup>-2</sup> for DIF2, against 0.62,
- <sup>15</sup> 0.58, 0.72 kg m<sup>-2</sup> for FR-2L, DIF1, and DIF3, respectively). The same phenomenon happens in the DIF3 simulation to a lower extent. In particular, the DIF3  $B_{ag_X}$  is not very different from the FR-2L one. The DIF1 simulation is closer to FR-2L. When the root-zone soil moisture reaches the wilting point (equal to 0.17 m<sup>3</sup> m<sup>-3</sup> as indicated in Fig. 9 by the dashed line), the senescence starts. A marked water stress occurs and
- impacts photosynthesis and biomass production. Since water is supplied by the subroot zone soil layers of DIF2 and DIF3, the wilting point is reached later than for FR-2L and DIF1 and the senescence starts later.

In FR-2L, the growth of  $B_{ag}$  is faster than in the other simulations. This leads to a slightly higher value of  $B_{ag_x}$  than for DIF1. This is related to the lower FR-2L root-zone soil moisture in May. In the drought-avoiding C3 crop parameterization of ISBA-A-qs,

soil moisture in May. In the drought-avoiding C3 crop parameterization of ISBA-A-gs, a moderate soil moisture stress triggers an increase in water use efficiency (Calvet, 2000) and enhances plant growth.



#### 4 Discussion

# 4.1 Is the Jackson root profile model (Eq. 1) applicable at the local scale?

A difficulty in the implementation of DIF simulations is that the proposed  $R_{e}$  values in Eq. (1) are the result of a meta-analysis. A single  $R_{\rm e}$  value is proposed for a given vegetation type while a large variability of  $R_{e}$  can be observed. This is particularly true for crops, and Fig. 1 in Jackson et al. (1996) shows that  $Y(d_1)$  and  $R_{e}$  present a much higher variability for crops than for temperate grasslands. This difficulty may explain the shortcomings of DIF1 simulations for the 61-Orne département described in Sect. 3.2.1 (Table 3). In particular, the root density in the top soil layers has a large impact on the water stress modelling. This is demonstrated by performing an additional DIF1 simulation (DIF1-Uniform) using a uniform root density profile instead of Eq. (1). Figure 10 shows the evolution of  $B_{aq}$ , SWI<sub>top</sub>( $d_{B}$ ) and SWI<sub>top</sub> (0.46 m) for the FR-2L, DIF1 and DIF1-Uniform simulations for the 61-Orne département over the period from April to July 1999. For all the simulations,  $g_m = 1.75 \text{ mm s}^{-1}$  and MaxAWC = 225 mm. The  $B_{aq}$  evolution during the first three months is similar in the three simulations, with 15 a slightly faster growth for FR-2L. However, while senescence occurs on mid-July for DIF1, it occurs only at the end of July for FR-2L and DIF1-Uniform. The early senescence for DIF1 is related to values of SWI<sub>top</sub> getting close to zero at the top fraction of the root-zone: while  $SWI_{top}$  (0.46 m) decreases below the 0.3 critical soil moisture content value (Table 1) at the beginning of July, for DIF1, it never gets below 0.3 in July 20 for DIF1-Uniform. Finally, the  $B_{ag_x}$  value for FR-2L and DIF1-Uniform is higher than for DIF1. This root profile effect also has an impact on the interannual variability and partly explains the lower  $R^2$  value for DIF1 in Table 3 for this site.

#### 4.2 Impact of the representation of the vegetation canopy

<sup>25</sup> Table 2 shows that while the DIF1-NRT results are close to those of DIF1 for grasslands, DIF1-NRT tends to outperform DIF1 for C3 crops. Figure 11 presents the



simulated  $B_{aq}$  of C3 crops and grasslands for the DIF1 and DIF1-NRT simulations in the 61-Orne département over the 1994-2010 period. The two grassland simulations are very similar. On the other hand, the two C3 crop simulations differ in  $B_{aq_x}$ 

- values. The mean simulated  $B_{ag_{\chi}}$  values for C3 crops are 1.61 kg m<sup>-2</sup> and 1.32 kg m<sup>-2</sup> for DIF1 and DIF1-NRT, respectively. The lower  $B_{ag_{\chi}}$  values simulated by DIF1-NRT are related to the lowest gross primary production simulated by this version of the ISBA-Ags model (Carrer et al., 2013). Also, DIF1-NRT simulates shorter growing periods and a slightly enhanced interannual variability: the ACV (see Sect. 2.7) is equal to 7.4 % for DIF1, and to 8.4 % for DIF1-NRT. For grasslands, the mean simulated  $B_{aq_v}$  values are
- 0.46 and 0.44 kg m<sup>-2</sup> for DIF1 and DIF1-NRT, respectively, and ACV values for DIF1 and DIF1-NRT are both equal to 30%.

#### Can a generic model be used to simulate the relative gain or loss of 4.3 agricultural production during extreme years?

While the main objective of this work is to evaluate contrasting root water uptake models using agricultural statistics, it can be investigated how the resulting  $B_{aq_v}$  values react to extreme years (either favourable or unfavourable to agricultural production). The best simulations result from the local optimisation of the MaxAWC parameter. Selecting the sites where the optimisation is successful, i.e. where the correlation between  $B_{ag_x}$ and GY or DMY is significant (p value < 0.01), the time series of the mean  $B_{aq_y}$  and mean GY and of the mean  $B_{ag_x}$  and mean DMY are compared in Fig. 12 for both  $\hat{F}R-2L$ 20 and DIF1-NRT experiments. The interannual variability of the grassland DMY is better represented by  $B_{ag_{X}}$  than for the cereal GY, with  $R^{2} = 0.83$  and  $R^{2} = 0.45$ , respectively. The FR-2L experiment presents slightly better  $R^2$  values than DIF1-NRT. For C3 crops, it appears that the two experiments are not able to represent the lower GY in 2007, nor the higher GY in 2004. For grasslands, the two experiments are not able to 25 represent the lower DMY in 1996. Table 4 summarizes the true and false detection of favourable and unfavourable years. The latter are defined as  $A_{S,B_{aav}}$  or  $A_{S,DMY}$  values



higher (lower) than 1.0 (-1.0). The  $A_{S,B_{any}}$  or  $A_{S,DMY}$  values are based on the mean time series of Fig. 12. The undetected favourable and unfavourable years are also listed in Table 4. The best detection performance is obtained by DIF1-NRT for grasslands, with only 1996 not detected as unfavourable. The worst detection performance is obtained by DIF1-NRT for C3 crops, with 2003 and 2007 not detected as unfavourable, 1998 and 2004 not detected as favourable, 1997 wrongly detected as unfavourable, and 2008 wrongly detected as favourable. For grasslands, the extreme years, defined as A<sub>S,DMY</sub> values higher (lower) than 1.5 (-1.5), are 2007 (favourable) and 2003 (unfavourable). These two cases are correctly identified in the two experiments. For C3 crops, the most favourable years are 2002 and 2009 and the most unfavourable year is 2007. While 2002 and 2009 are correctly identified in the two experiments, 2007 is

- not detected. The higher performance in the representation of extreme years for grasslands than for C3 crops is consistent with the results of Table 2 showing that significant correlations between  $B_{ag_x}$  and DMY are obtained more often than between  $B_{ag_x}$  and
- GY. This can be explained by the more pronounced interannual variability of the grass-15 land DMY, with ACV = 30% against ACV values less than 10% for the cereal GY. The highest sensitivity of grasslands to climatic conditions is related to their growing cycle covering a longer period than cereals, and to their MaxAWC values, generally lower than for cereals (Table 2). Finally, ISBA-A-gs has no direct representation of agricul-
- tural practices and of the cereal GY and the consistency between  $B_{ag_x}$  and GY relies 20 on the hypothesis that the harvest index (the ratio of GY to  $B_{ag_x}$ ) does not vary much from one year to another at the considered spatial scale. This issue is discussed in Ca12. For grasslands, the simulated  $B_{aq_y}$  is more directly representative of DMY. This explains why a better agreement of the simulations is found with the grassland DMY
- than with the cereal GY (Tables 2 and 4).

#### Prospects for better constraining MaxAWC at various scales 4.4

In addition to the intrinsic limitations related to the use of a generic LSM, unable to represent agricultural practices (see above), uncertainties are generated by the datasets



used to force the LSM simulations. For example, the incoming radiation is SAFRAN can be affected by seasonal biases (Szczypta et al., 2011; Carrer et al., 2012), and the coarse spatial resolution of agricultural statistics prevents the use of local soil properties (Sect. 2.3). Since phenology in ISBA-A-gs is driven by photosynthesis, biases

- <sup>5</sup> in the incoming radiation can impact the date of the leaf onset. The impact of errors in the forcing data is probably more acute for cereals than for grasslands in relation to a shorter growing period. More research is needed to assess the impact of using enhanced atmospheric reanalyses (Weedon et al., 2011; Oubeidillah et al., 2014) and proxies for annual agricultural statistics such as gridded maximum LAI values at a spatial resolution of 1 km w 1 km derived from establish products (Paret et al., 2012)
- tial resolution of 1 km × 1 km derived from satellite products (Baret et al., 2013).

#### 5 Conclusions

The observed cereal GY and permanent grassland DMY production in France from 1994 to 2010 was used in this study to evaluate four contrasting representations of the root water uptake in the ISBA-A-gs land surface model within SURFEX. A simple representation of the root-zone soil moisture based on a single bulk reservoir (FR-2L) was 15 compared with multilayer diffusion models describing the soil water uptake profile. The latter used the Jackson root vertical distribution equation, with and without additional subroot zone base flow soil layers. In order to limit the uncertainty related to the lack of knowledge of local rooting depth conditions, the MaxAWC quantity was retrieved by matching the simulated  $B_{ag_x}$  with the Agreste agricultural statistics, for given vegeta-20 tion and photosynthesis parameters. The impact on the results of the representation of the vegetation was assessed using another representation of the light absorption by the canopy and using refreshed values of the  $g_m$  photosynthesis parameter. The  $B_{aq_y}$  time series based on the multilayer model without additional subroot zone base flow soil layers presented correlations with the agricultural statistics similar to those ob-25 tained with FR-2L. On the other hand, adding subroot zone base flow soil layers tended to degrade the correlations. Overall, a better agreement of the simulations was found



with the grassland DMY than with the cereal GY in relation to several factors such as (1) the more pronounced interannual variability of the grassland DMY, (2) the more direct correspondence between  $B_{ag_X}$  and DMY, (3) less variability in the parameters of the Jackson model than for crops. More research is needed to map the MaxAWC parameter. In particular, long time series of satellite-derived vegetation products (e.g. GEOV1, Baret et al., 2013) could be used in conjunction with soil parameter maps to constrain MaxAWC.

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**Table 1.** Standard values of ISBA-A-gs parameters for C3 crops and grasslands (Gibelin et al., 2006).

Plant type	Cuticular conductance $(g_c) \text{ (mm s}^{-1})$	Critical extractable soil moisture content ( $\theta_c$ )	Response to drought	Maximum leaf span time ( $\tau_{\rm M}$ ) (days)	Minimum leaf area index (LAI <sub>min</sub> ) (m <sup>2</sup> m <sup>-2</sup> )	Leaf nitrogen concentration (N <sub>L</sub> ) (% of dry mass)	SLA sensitivity to N <sub>L</sub> (e) (m <sup>2</sup> kg <sup>-1</sup> % <sup>-1</sup> )	SLA at $N_{\rm L} = 0 \%(f)$ $(m^2 kg^{-1})$	Fraction of vegetation coverage (%)
C3 crops	0.25	0.3	Avoiding	150	0.3	1.3	3.79	9.84	100
grasslands	0.25	0.3	Tolerant	150	0.3	1.3	5.56	6.73	100

**Table 2.** Median  $g_m$  and MaxAWC values derived for each experiment (<sup>1</sup>) and number of sites where the simulated  $B_{ag_x}$  presents significant correlations (<sup>2</sup>) with the annual yields of Agreste statistics for six cereals (winter wheat, rye, winter barley, spring barley, oat and triticale) and for permanent grasslands in France over the 1994–2010 period.

Plant type			C3 cro	ps					grasslar	nds	
Experiment	FR-2L	DIF1	DIF2	DIF3	DIF1-NRT	FR	·2L	DIF1	DIF2	DIF3	DIF1-NRT
Median and standard deviation of optimal $g_{\rm m}  ({\rm mm  s}^{-1})$	<b>1.75</b> 0.40	<b>1.75</b> 0.53	<b>1.75</b> 0.51	<b>1.75</b> 0.53	<b>1.75</b> 0.56	<b>1.</b> 3 0.4	<b>38</b> 18	<b>1.38</b> 0.49	<b>1.50</b> 0.47	<b>1.25</b> 0.49	<b>1.25</b> 0.42
Median and standard deviation of optimal MaxAWC (mm)	<b>125</b> 54.0	<b>112.5</b> 61.3	<b>81.3</b> 84.0	<b>93.8</b> 63.0	<b>100</b> 64	<b>81</b> 55	<b>.3</b> .0	<b>68.8</b> 54.0	<b>75.0</b> 55.0	<b>75.0</b> 58.0	<b>75.0</b> 58.0
Number of sites			45						48		
Number of sites pre- senting significant correlations (at 1 % and 0.1 % level)	12–5	10–3	6–2	10–3	13–4	34-	-22	36–20	27–10	33–16	37–19

<sup>1</sup> A site-by-site optimisation of  $g_m$  is performed for FR-2L and DIF1-NRT only; DIF1, DIF2, and DIF3 use the same site-level  $g_m$  values as FR-2L.

<sup>2</sup> Significant correlations at 1 % and 0.1 % level correspond to coefficient of determination (R<sup>2</sup>) values higher than 0.366 and 0.525, respectively.



**Table 3.** Optimal MaxAWC and squared correlation coefficient ( $R^2$ ) between  $B_{ag_x}$  and Agreste for FR-2L and DIF1 simulations at sites where the same cereal Agreste data are used and where the correlation between  $B_{ag_x}$  values and the yields of Agreste statistics are significant at least at 1 % level. The highest MaxAWC and  $R^2$  values at a given site are in bold.

Exper	riment		FR-2L	DIF1		
Département	Cereal	$R^2$	Optimal Max- AWC (mm)	$R^2$	Optimal Max- AWC (mm)	
08	oat	0.60	87.5	0.63	75.0	
63	winter barley	0.60	112.5	0.63	112.5	
18	rye	0.57	225.0	0.54	225.0	
86	oat	0.52	87.5	0.51	87.5	
11	winter barley	0.53	125.0	0.49	112.5	
16	oat	0.46	100.0	0.41	62.5	
91	spring barley	0.42	137.5	0.40	112.5	
61	triticale	0.53	200.0	0.40	225.0	



Table 4. Correspondence between simulated and observed extreme years for sites with signif-
icant correlations (R <sup>2</sup> ) at the 1 % level with both FR-2L and DIF1-NRT simulations for C3 crops
and grasslands as shown in Fig. 12. Favourable (unfavourable) years are defined as z scores
$A_{S,B_{any}}$ or $A_{S,DMY}$ higher (lower) than 1.0 (-1.0). Years with $A_{S,DMY}$ higher (lower) than 1.5 (-1.5)
are in bold.

		Favourable		Unfavo	ourable	Norma	l (false)
Plant type	Experiment	True False		True	False	while favourable	while un- favourable
C3 crops	FR-2L DIF1-NRT	2002, 2008, 2009 2002, 2009	2008	2001	1997, 2010 1997	2004 1998, 2004	2001, <b>2007</b> 2003, <b>2007</b>
grasslands	FR-2L DIF1-NRT	<b>2007</b> , 2008 2000, <b>2007</b> , 2008	2000	<b>2003</b> , 2010 <b>2003</b> , 2010			1996 1996





**Figure 1.** Location of the 45 cropland and 48 grassland 8km × 8km grid cells (blue and green dots, respectively) and the corresponding département number.









# DIF1



**Figure 3.** Soil profile of the DIF1 experiment. The soil depth within the root-zone is in meters. Only two configurations are represented: for the minimum (left panel) and maximum (right panel) values of MaxAWC (50 and 225 mm, respectively). The cumulative root density profile for crops (Eq. 1 with  $R_{\rm e}$  = 0.961) is represented by a brown line. A top soil layer of 1 cm is represented.



DIF2



Figure 4. As in Fig. 3, except for DIF2 experiment. Subroot soil layers are added (blue lines), down to a constant soil depth of 1.96 m.





DIF3

**Figure 5.** As in Fig. 3, except for DIF3 experiment. Two subroot soil layers of 10 cm are added (blue lines).











**Figure 7.** As in Fig. 6, except for grasslands ( $g_m = 0.5 \text{ mm s}^{-1}$ , MaxAWC = 50 mm).





**Figure 8.** Best FR-2L simulations vs. Agreste statistics correlation levels obtained for (left panel) C3 crops and (right panel) grasslands. Non-significant, significant at the 1% level and significant at the 0.1% level correlations are indicated in red squares, yellow dots and black dots, respectively.





**Figure 9.** Simulations in 1996 for C3 crops ( $g_m = 0.5 \text{ mm s}^{-1}$ , MaxAWC = 75 mm) in the 08-Ardennes département of (top panel) above-ground biomass and (bottom panel) root-zone soil moisture in the DIF1, DIF2, DIF3 and FR-2L configurations (red solid, red dotted, red dashed, and black lines, respectively). The grey lines indicate the root-zone soil moisture values at field capacity and at wilting point.





**Figure 10.** Simulations in 1999 for C3 crops ( $g_m = 1.75 \text{ mm s}^{-1}$ , MaxAWC = 225 mm,  $d_R = 1.76 \text{ m}$ ) in the 61-Orne department of (top panel) above-ground biomass, and (bottom panel) SWI<sub>top</sub>( $d_R$ ) for FR-2L (black line), DIF1 (red solid line), and DIF1-Uniform (red dotted line), and SWI<sub>top</sub> (0.46 m) for DIF1 (blue solid line) and DIF1-Uniform (blue dotted line).











**Figure 12.** Averaged simulated yearly  $B_{ag_x}$  values (ISBA-A-gs, solid lines) and averaged observed agricultural yields (Agreste, dashed lines) for sites with significant correlations ( $R^2$ ) at the 1 % level with both FR-2L (black solid line) and DIF1-NRT (red solid line) simulations for (top panel) C3 crop GY and (bottom panel) grassland DMY.

