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Use of agricultural statistics to verify the internannual variability in land surface models: a case study over France with ISBA-A-gs

J.-C. Calvet[1], S. Lafont[1], E. Cloppet[2], F. Souverain[2], V. Badeau[3], and C. Le Bas[4]

[1]CNRM/GAME, Météo-France, CNRS, URA 1357, 42 avenue Coriolis, 31057 Toulouse Cedex 1, France
[2]Météo-France, Direction de la Production, 42 avenue Coriolis, 31057 Toulouse Cedex 1, France
[3]Ecologie et Ecophysiologie Forestière, INRA, UHP, Nancy, France
[4]Unité 1106 Infosol, INRA, Orléans, France

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Correspondence to: J.-C. Calvet (calvet@meteo.fr)

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Abstract

In order to verify the interannual variability of the above-ground biomass of herbaceous vegetation simulated by the ISBA-A-gs land surface model, within the SURFEX modelling platform, French agricultural statistics for C3 crops and grasslands were compared with the simulations for the 1994–2008 period. While excellent correlations are obtained for grasslands, representing the interannual variability of crops is more difficult. It is shown that, the Maximum Available soil Water Capacity (MaxAWC) has a large influence on the correlation between the model and the agricultural statistics. In particular, high values of MaxAWC tend to reduce the impact of the climate interannual variability on the simulated biomass, and to allow the simulation of a negative trend in biomass production, in relation to a marked warming trend, of about 0.12 $\mathrm{K\,y^{-1}}$ on average, affecting the daily maximum air temperature during the growing period (April–June), especially in northern France. The estimates of MaxAWC for C3 crops and grasslands, currently used in SURFEX, are about 129 mm and do not vary much. Therefore, more accurate grid-cell values of this parameter are needed.

1 Introduction

SURFEX (Surface Externalisée) is a surface modelling platform developed by Meteo-France (www.cnrm.meteo.fr/surfex/) including specific models for soil/vegetation processes, urban areas, water bodies and ocean, together with interfaces with atmospheric and hydrological models (Martin et al., 2007; Le Moigne et al., 2009). Over land, SURFEX uses the Interactions between Soil, Biosphere and Atmosphere (ISBA) Land Surface Model (LSM), described in Noilhan and Planton (1989), and Noilhan and Mahfouf (1996). Also, SURFEX includes the carbon module of ISBA, ISBA-A-gs (Calvet et al., 1998; Calvet and Soussana, 2001; Gibelin et al., 2006).

The added value of ISBA-A-gs is the possibility to simulate the CO_2 fluxes, in conjunction with the water and energy fluxes and state variables simulated by the model.

In particular, the vegetation transpiration calculated by ISBA-A-gs is related to a photosynthesis model able to describe the impact of drought (Calvet, 2000; Calvet et al., 2004). Moreover, an option of ISBA-A-gs permits to simulate the vegetation biomass and Leaf Area Index (LAI). This option is useful for climate change impact studies (Calvet et al., 2008), and allows the sequential assimilation of satellite LAI estimates (Sabater et al., 2008; Albergel et al., 2010; Barbu et al., 2011).

Another advantage of ISBA-A-gs is that the simulated CO_2 fluxes can be validated along with the evapotranspiration using the extensive in situ flux observations of the FLUXNET initiative, gathering more than 500 sites worldwide (www.fluxdata.org). This was illustrated by Gibelin et al. (2008) for mid-latitudes.

However, the interannual variability of the above-ground biomass (B_{ag}) and of the LAI simulated by ISBA-A-gs is not easy to verify (Brut et al., 2009). The vegetation biomass is not directly observed so far by Earth observation satellites, and the satellite-derived LAI values are affected by a saturation phenomenon at high LAI values, inducing a high uncertainty on yearly maximum LAI values (Garrigues et al., 2008). Therefore, in situ observations related to the vegetation biomass are needed. For crops, the agricultural statistics can be used, as shown by Smith et al. (2010a, b) at the country level in Europe, with the ORCHIDEE (Krinner et al., 2005) LSM and the STICS (Brisson et al., 1998) crop model. They worked over the period 1972–2003, marked by a very strong increase in crop yields all over Europe caused by more and more intensive crop management practices (use of fertilizers, pesticides, more productive cultivars). In order to extract the interannual variability signal from the yield time series, they de-trended the crop yields using a linear trend curve, and they analyzed the standard deviation of the de-trended yield anomalies, only.

In this study, an attempt is made to use the detailed agricultural dry matter yield statistics available in France (Agreste, 2011) for relatively small administrative units (“départements”) ranging from 2000 km^2 to 10 000 km^2. In order to analyze the year-to-year variability of the modelled biomass production, we focus on the 1994–2008 period. This 15-yr period is characterized in France (Gate et al., 2010; Brisson, 2010), as in many European countries, by crop yields presenting little or no trend. The objective is to assess to what extent this information can be used to validate a generic LSM able to represent the climate impact on the main biophysical processes using a limited number of equations and parameters, but unable to simulate the crop grain yield formation per se. Indeed, while ISBA-A-gs simulates the climatic impacts on photosynthesis and on the vegetation growth, specific factors impacting the agricultural production are not accounted for. The latter include changes in the intensity of the crop management (in relation to technical advances or public policies), pests, diseases, migration of a given crop type from productive to poorer lands, or (in the case of cereals) the grain formation. An important aspect of the validation is the verification of the hypothesis made in SURFEX on the value of the Maximum Available soil Water Content (MaxAWC), on photosynthesis parameters, and on specific plant responses (avoiding or tolerant) to drought. Three contrasting categories of agricultural products described by Agreste were considered: cereals, forage pea, and grass.

The ISBA-A-gs parameters and the available atmospheric and agricultural data over specific regions in France are presented in Sect. 2, for C3 crops (cereals and forage pea in this study) and grasslands. The impact of the ISBA-A-gs parameters on the interannual variability of the simulated B_{ag} is presented in Sect. 3, together with the parameter values optimizing the correlation with agricultural statistics. It is shown to what extent the B_{ag} simulated by the model is consistent with the agricultural statistics. Finally, the results are discussed in Sect. 4, and the main conclusions are summarized in Sect. 5.

2 Material and methods

2.1 Parameters of ISBA-A-gs and studied sites

ISBA-A-gs uses a CO_2 responsive parameterization of photosynthesis based on the model of Goudriaan et al. (1985) modified by Jacobs (1994) and Jacobs et al. (1996).

This parameterization differs from the set of equations commonly used in other land surface models (Farquhar et al., 1980 for C3 plants and Collatz et al., 1992 for C4 plants), and it has the same formulation for C4 plants as for C3 plants, differing only by the input parameters. The model also includes a detailed representation of the soil moisture stress. Two different types of drought responses are distinguished for both herbaceous vegetation (Calvet, 2000) and forests (Calvet et al., 2004), depending on the evolution of the water use efficiency (WUE) under moderate stress: WUE increases in the early soil water stress stages in the case of the drought-avoiding response, whereas WUE decreases or remains stable in the case of the drought-tolerant response.

Table 1 presents the standard values of ISBA-A-gs parameters (Gibelin et al., 2006) used in the SURFEX modelling platform, for C3 crops and for C3 grasslands. The photosynthesis model is governed by four key parameters: the mesophyll conductance in well-watered conditions, g_m, the cuticular conductance, g_c, the critical extractable soil moisture content, θ_C, and the response to drought (drought-avoiding or drought-tolerant). The latter is (in Table 1) the only parameter distinguishing the standard photosynthesis parameters for C3 crops and C3 grasslands. Plant growth is characterized by five parameters: the maximum leaf span time, τ_M, the minimum leaf area index $\mathrm{LAI}_\mathrm{min}$, the leaf nitrogen concentration N_L, the SLA (specific leaf area) sensitivity to N_L, e, and SLA at $N_L = 0\,\%$, f. The latter two differ from C3 crops to C3 grasslands (Table 1).

The value of MaxAWC may change from one location to another, depending on soil and plant characteristics: soil moisture at field capacity, soil moisture at wilting point, and rooting depth. These parameters, together with the fraction of vegetation types, are provided by the ECOCLIMAP global database (Masson et al., 2003), at a spatial resolution of 1 km. ECOCLIMAP is a database of key surface parameters (soil texture, albedo, emissivity, roughness length, LAI, vegetation fraction, and physiological parameters) for land surface modelling. Over France, more often than not, the ECOCLIMAP classes correspond to a combination of 6 main patches (bare soils, coniferous trees, deciduous broadleaf trees, C3 crops, C4 crops, C3 grasslands). An updated version of ECOCLIMAP (ECOCLIMAP-II) is now available over Africa (Kaptué Tchuenté et al., 2010, 2011), and over Europe (Faroux et al., 2009). It is based on more recent input satellite data (several years of SPOT/VEGETATION NDVI) and distinguishes, also, crops growing at springtime (e.g. wheat) from crops growing at summertime (e.g. maize, sunflower).

In this study, C3 crops growing at springtime are considered, as they are generally rainfed and as such, their yield interannual variability is more markedly related to climatic conditions. Also, permanent grasslands below 1000 m a.s.l. are considered, only, as high altitude grasslands are represented with difficulty by ISBA-A-gs (Brut et al., 2009). Also, the ISOP (Information et Suivi Objectif des Prairies) model-based grassland production index considered in this study (Sect. 2.3.2) is not available above 1000 m a.s.l. (Ruget et al., 2006).

Figure 1 presents the location of the studied sites, for both C3 crops and grasslands. They correspond to ECOCLIMAP-II grid cells presenting, in a given “département” administrative unit, the highest fraction of either C3 crops or grasslands. At these sites, the C3 crop or grassland patches represent at least 45 % of the ECOCLIMAP-II grid cell.

2.2 Forcing atmospheric data

A high-resolution (8 km) atmospheric forcing data set is available for simulations over France. It is provided by the atmospheric analysis system “Système d’Analyse Fournissant des Renseignements A la Neige” (SAFRAN) (Durand et al., 1993, 1999). SAFRAN is a mesoscale atmospheric analysis system for surface variables. It produces an analysis of air temperature, air humidity, wind speed, incoming shortwave and longwave radiations at the hourly time step, and an analysis of precipitation at the daily time step, using atmospheric simulations and ground data observations. SAFRAN is based on climatically homogeneous zones and is able to take topography effects into account. Originally intended for mountainous areas, it was later extended to cover

France. A detailed validation of the SAFRAN analysis over France (Quintana et al., 2008) showed that SAFRAN provides accurate meteorological values to force LSM. In particular, SAFRAN uses a large number of rain gauges and can be considered as a reference for the verification over France of global precipitation analyses (Szczypta et al., 2011).

Over the studied sites (Fig. 1), and for the 1994–2008 period, SAFRAN presents a marked positive trend of the average maximum air temperature for April-May-June, i.e. for the start of the growing period:

- For C3 crops sites, the trend is systematically positive (ranging from 0.015 Ky^{-1} to 0.183 Ky^{-1}), and the average value is 0.126 Ky^{-1}.
- For grassland sites, the trend ranges from –0.001 Ky^{-1} to 0.186 Ky^{-1}, and the average value is 0.118 Ky^{-1}.

This trend is more acute in northern France.

2.3 The French agricultural statistics

2.3.1 Crops

The French agricultural annual statistics are freely available on the web, at the "département" administrative level (Agreste, 2011). They are based on extensive local to national observations of harvested grain quantities. In this study, the Agreste data for the 1994–2008 15-yr period were considered, only. The considered C3 crops were 6 types of cereals (winter wheat, rye, winter barley, spring barley, oat, triticale) and forage pea. All these crops cover significant land surfaces in 45 départements (Fig. 1).

Figure 2 shows the dry matter yield time series provided by Agreste for cereals and forage pea, from 1994 to 2008. The data are shown for each département, together with the average curve. No significant trend of the average yield is observed, except for forage pea, with a significant (at the 1 % level) negative trend of –6.15 $\mathrm{gm}^{-2}\,\mathrm{y}^{-1}$.

2.3.2 Grasslands

Agreste provides dry matter yield annual values for both permanent and temporary grasslands. In this study, low altitude permanent grasslands were studied for 48 départements (Fig. 1). In Agreste, permanent grasslands are defined as natural grasslands or as planted grasslands older than 6 yr. Also, since 2000, Météo-France has issued the ISOP index (Ruget et al., 2006), based on simulations of the STICS model of Institut National de la Recherche Agronomique (INRA), driven by daily atmospheric variables derived from interpolated ground observations of meteorological variables. The ISOP index used in this study is the ratio of the annual grass production simulated by STICS, for permanent grasslands, to the average value simulated for the period 1982-2006, at a given location. In contrast to Agreste, ISOP is not provided at the département level, but for specific forage regions. The 48 grassland sites presented in Fig. 1 were derived from the département limits and from the ECOCLIMAP-II grassland fraction, and the corresponding ISOP regions were used. In the ISOP-STICS simulations, the grass is regularly cut, from January to October, and the cut biomass is cumulated throughout the year in order to calculate the annual dry matter yield. The harvest dates depend on climatic conditions and are derived from temperature sums.

Figure 3 shows the dry matter yield time series provided by Agreste for grasslands, together with the ISOP index (at the corresponding forage regions), from 1994 to 2008. The data are shown for each département, together with the average curve. No significant trend of the average yield is observed. ISOP presents a more pronounced interannual variability than the Agreste statistics, especially before 2000. After 2000, the ISOP index information was incorporated into the Agreste statistics, and the correlation between the two estimates increased sharply.

2.4 From ISBA-A-gs to the agricultural statistics

The ISBA-A-gs simulations are driven by SAFRAN hourly atmospheric variables. C3 crops and grasslands are simulated using the standard parameters of

Table 1. Continuous simulations were performed from 1994 to 2008, for all the sites presented in Fig. 1. As a preliminary sensitivity study (see Sect. 3.1) has shown that the interannual variability of the simulated B_{ag} is very sensitive to the g_m key photosynthesis parameter and to MaxAWC, the 15-y simulations were repeated 48 (8 × 6) times for each site:

- 8 MaxAWC values were used: 50, 75, 100, 125, 150, 175, 200, 225 mm,
- 6 g_m values were used: 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 mm s^{-1}.

Standard ISBA-A-gs simulations do not include a description of agricultural management practices, and vegetation growth is driven by photosynthesis and by the climatic factors (including drought) acting on photosynthesis. Plant growth corresponds to the net assimilation of CO_2 by photosynthesis, and plant mortality is induced by a deficit of photosynthesis (with respect to an optimal photosynthesis level depending on model parameters). However, a simple irrigation model (Calvet et al., 2008) may be activated, together with the possibility to prescribe an emergence date (by artificially maintaining LAI at its minimum value, LAI_{min}, presented in Table 1). In this study, these options were not activated. For grasslands, cuts can be prescribed at given dates (Calvet and Soussana, 2001) or when LAI has reached a predefined threshold. In this study, both unmanaged and managed grasslands were simulated. In the latter simulations, cuts were simulated when LAI reached a value of $2\,\text{m}^2\,\text{m}^{-2}$.

Figures 4 and 5 present ISBA-A-gs simulations of B_{ag} and AWC, for C3 crops and grasslands, respectively. The C3 crop and grassland simulations are performed for the SAFRAN grid cells located in the Puy-de-Dôme administrative unit (45.94 N, 3.21 E, and 46.23 N, 2.91 E, respectively), for MaxAWC values of 175 mm and 100 mm, respectively. The model parameters are those presented in Table 1, except for $g_m = 0.75\,\text{mm}\,\text{s}^{-1}$ for unmanaged grasslands, and $g_m = 1.25\,\text{mm}\,\text{s}^{-1}$ for managed grasslands. Despite the enhanced photosynthesis and plant transpiration triggered by the higher g_m value, the managed grasslands tend to evaporate less than the unmanaged grasslands because LAI does not exceed 2 $\mathrm{m}^2\,\mathrm{m}^{-2}$ (against annual maximum LAI values ranging from 4.3 $\mathrm{m}^2\,\mathrm{m}^{-2}$ to 6.0 $\mathrm{m}^2\,\mathrm{m}^{-2}$ for the unmanaged grassland).

The variables compared with the agricultural statistics are: (1) for the C3 crops and the unmanaged grasslands, the annual maximum B_{ag}, (2) for managed grasslands, the cumulated cut biomass throughout the annual cycle.

3 Results

3.1 Key ISBA-A-gs parameters impact the biomass interannual variability

The ISBA-A-gs model is not a crop model and as such, does not simulate the agricultural practices in detail, nor the intensity of the crop management, pest control, crop rotation, or (in the case of cereals) the grain formation. The main factor governing the annual maximum B_{ag}, at the end of the growing season, is the soil moisture stress caused by low AWC values. The latter can be caused by low MaxAWC values, and/or by high evaporation rates through stomatal or non-stomatal (cuticular) leaf transpiration, governed by the g_m and g_c parameters, respectively.

The sensitivity of the squared correlation coefficient (R^2) of the annual C3 crop maximum B_{ag} simulated by ISBA-A-gs vs. the Agreste yield statistics was investigated over the Haute-Garonne administrative unit (SAFRAN grid cell at 43.57 N, 1.79 E), for various values of key parameters governing the soil moisture stress: MaxAWC, g_m, θ_C and g_c. A large range of parameter values, different from their reference standard values in Table 1, was explored. The parameters were tested one by one (i.e. the other parameters kept their standard value). A reference MaxAWC of 120 mm was used. Over Haute-Garonne, good correlations are found for rye and the Agreste yield time series for rye was used to calculate the R^2 values. Figure 6 shows the result of the sensitivity study. The values of MaxAWC and g_m parameters markedly impact R^2. The response to the MaxAWC parameter is particularly marked. For extreme values of these two parameters, R^2 values close to zero are found. On the other hand, changes in g_c,

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

and (especially) θ_C, do not impact R^2 much. As this result indicates that the agricultural statistics may help constraining average values of MaxAWC and g_m, the values of these parameters were explored in detail as described in Sect. 2.4. For each administrative unit, and for each crop type (cereals, forage pea, and grasslands), optimal values of MaxAWC and g_m were obtained, i.e. values providing the best correlation between the agricultural yield statistics and the simulated biomass production. Table 2 presents the median values of the optimum MaxAWC and g_m for cereals, forage pea, and grasslands.

A noticeable property of MaxAWC is its influence on the amplitude of the interannual variability of the annual maximum biomass simulated by ISBA-A-gs. For example, the optimal MaxAWC value obtained for managed grasslands using ISOP (Table 2) is lower than the value obtained using Agreste (100 mm and 125 mm, respectively), consistent with the more pronounced interannual variability of the ISOP index. This phenomenon is observed for C3 crops, also. Figures 7 and 8 present the simulated annual maximum biomass of cereals and forage pea, respectively. While the median retrieved values of g_m, 1 mm s^{-1} and 1.5 mm s^{-1}, respectively, are used, several MaxAWC values are explored. It is shown that low values of this parameter tend to increase the interannual variability. For high values, a negative trend appears, for both cereals and forage pea, as the impact of the climatic trend is no longer masked by a strong interannual variability. From this point of view, the high optimal MaxAWC value obtained for forage pea (200 mm) is consistent with the significant negative trend observed by Agreste for this crop (Sect. 2.3.1).

3.2 The interannual variability is more accurately simulated for grasslands than for C3 crops

The R^2 score used in Sect. 3.1 was optimized for all the studied sites by tuning the MaxAWC and g_m parameters, with the other model parameters remaining constant at values indicated in Table 1. Figures 9 and 10 present maps of three R^2 levels (non-significant, significant at the 1 % level, significant at the 0.1 % level) for C3 crops (cereals and forage pea) and grasslands (unmanaged and managed), respectively, and the results are summarized in Table 2. For cereals, 6 crops are considered (i.e. winter wheat, rye, winter barley, spring barley, oat, triticale, in this study), and the highest R^2 at a given location is used in Fig. 9 and in Table 2. In Fig. 10, the ISOP index is shown together with Agreste, as slightly better correlations are obtained with ISOP. A striking result is the excellent scores obtained for managed grasslands with 44 of 48 sites presenting highly significant correlations (at the 0.1 % level) with ISOP, and the rather poor performance obtained for C3 crops with 5 forage pea sites (over 45) presenting highly significant correlations with Agreste. In the latter case, however, 20 sites present significant correlations (at the 1 % level) with Agreste. Generally, better results are obtained for forage pea than for cereals, and for managed grasslands than for unmanaged grasslands.

Another interesting result is that the default drought responses (Table 1) present better results than the alternative options, for both C3 crops and grasslands (Table 2).

3.3 Consistency between the simulated biomass and the agricultural statistics

Figure 11 presents the simulated B_{ag} vs. the Agreste grain yield of cereals and forage pea. The ratio of crop yield to the maximum B_{ag} is called the harvest index. For cereals and for forage pea, the harvest indices derived from Fig. 11 range between 20 % and 50 %, and between 20 % and 40 %, respectively. Overall, this is consistent with Bondeau et al. (2007), giving typical harvest index values for temperate cereals ranging from 20 % to 40 %.

Figure 12 presents the simulated harvested grass vs. the Agreste and ISOP-STICS yield estimates. The results are shown for the two options of the ISBA-A-gs model available for grasslands: unmanaged and managed. Table 3 displays the corresponding statistical scores. The best correlation is obtained for the unmanaged option of the model vs. Agreste ($r^2 = 0.70$). In this case, however, the simulated annual maximum B_{ag} is markedly overestimated by the model, by 0.17 kg m^{-2}, on average. Less scattering is obtained for the managed option of the model vs. ISOP-STICS, with a standard deviation of differences (SDD) of 0.17 kg m^{-2}. However, the model tends to produce lower yields than ISOP-STICS, with a mean bias of –0.23 kg m^{-2}.

4 Discussion

4.1 Sensitivity to g_m and to MaxAWC

The results of Sect. 3.1 show that two key parameters of the ISBA-A-gs model have a large impact on the simulated interannual variability of B_ag: g_m and MaxAWC. While MaxAWC may vary from one site to another, in relation to soil characteristics, large changes in g_m are not expected for intensively cultivated crops, as this parameter governs the intrinsic photosynthesis properties, at a given level of nutrient (e.g. nitrogen) availability. In order to assess the relative impact of the optimized two parameters, Table 2 indicates the number of sites presenting significant R^2 score with either g_m or MaxAWC, or both, assumed to be constant in space and equal to their median optimal value. Also, the loss in R^2 score caused by these assumptions is shown in Table 2. It is found that the detrimental impact on the simulated interannual variability of B_ag of prescribing a constant parameter value is systematically higher with a constant MaxAWC than with a constant g_m. Also, the model sensitivity varies from one vegetation type to another. Cereals are particularly sensitive to the use of local MaxAWC, as only 4 sites are correlated at the 1 % level with Agreste with a constant MaxAWC (against 13 sites with local MaxAWC values). Forage pea is less sensitive than cereals but the impact of using a constant MaxAWC is still marked (11 against 20 sites). On the other hand, the number of managed grasslands correlating at the 1 % level with ISOP presents little sensitivity to the two parameters. More sensitivity is found for the unmanaged grasslands, especially vs. Agreste. The lower sensitivity observed for managed grasslands may be related to the lower evapotranspiration caused by the LAI limitation imposed by the vegetation cuts. As the use of the soil moisture reservoir is reduced (Fig. 5), prescribing an accurate MaxAWC value is less critical.

4.2 C3 crops: why are the results that heterogeneous?

Table 2 and Fig. 9 show that the R^2 scores obtained for C3 crops are extremely heterogeneous. While a few sites present highly significant correlations (e.g. Puy-de-Dôme for both cereals and forage pea), the majority present no significant correlations. These contrasting results may be related to the heterogeneity of the agricultural practices and of the soil types in a particular administrative unit. From this point of view, the Puy-de-Dôme presents less heterogeneity, with most C3 crops concentrated in the "Limagne" plain, surrounded by hilly areas. Also, cereals may be irrigated in some regions, while rainfed crops are represented by the model simulations.

4.3 Are trends in forage pea production due to climate or to management intensity trends?

As shown in Sect. 2.2, the selected agricultural regions are affected by a marked warming trend of the growing season, during the 1994–2008 period, especially in northern France. In Sect. 3.1, it was shown that MaxAWC impacts the simulated trend in B_{ag}, as higher values of this parameter tend to limit the impact of the interannual variability and to favour the impact of the climatic trend. Therefore, the observed negative trend in the Agreste forage pea yields can be explained by high values of MaxAWC (with a median value of 200 mm in Table 2, against 175 mm for cereals), associated to the observed climatic trend. Other explanations can be proposed ("Pois", Wikipedia, http://fr.wikipedia.org/w/index.php?title=Pois&oldid=66239238, last access June 2011). In particular, the amount of agricultural lands devoted to forage pea in France has been decreasing from 6669 km^2 in 1994 to 1002 km^2 in 2008, in relation to less favourable public incentives to the cultivation of forage pea, and to the rapid extension in France of a specific disease caused by a fungus (*Aphanomyces euteiches*). These factors may have triggered changes in the distribution of MaxAWC values related to forage pea, and a less intensive cultivation of forage pea (e.g. use of poorer lands, and/or less fertilizers and pesticides). Since these factors are not accounted for by the model, and as the model is able to account for climatic factors only, the resulting MaxAWC obtained in this study for forage pea may be overestimated.

The reverse is true as the stable yields observed for cereals during the 1994–2008 period may be due to a progression of the intensification able to compensate for the climatic trend (Gate et al., 2010; Brisson, 2010). In this case, our optimized model would tend to underestimate the optimum MaxAWC.

This shows that MaxAWC "retrieved" values from agricultural statistics have to be evaluated.

4.4 Is the retrieved MaxAWC realistic?

The MaxAWC values obtained in this study can be compared with independent estimates:

- values for the rooting zone of the three-layer force-restore soil model currently used in SURFEX,
- values derived from a high resolution map of the soil characteristics developed by INRA, and aggregated within the SAFRAN grid cells in three subgrid categories: "minimum", "average", "maximum". Specific values of MaxAWC are derived for the soil types present in the SAFRAN grid cell. The average MaxAWC corresponds to a linear mixing of the specific MaxAWC values, weighted by the fractional cover of each soil type. Table 4 presents the various MaxAWC estimates, for cereals, forage pea, and managed grasslands sites for which a significant correlation (at the 1 % level) with agricultural statistics is achieved. The SURFEX median MaxAWC values do not vary from one vegetation type to another and are all equal to 129 mm. The standard deviations are small and do not exceed 10 mm. Indeed, except for sandy soils, the pedotransfer functions currently used in SURFEX (Noilhan and Mahfouf, 1996), tend to produce little variation of the difference between the field capacity soil moisture and the wilting point (FC-WP), which ranges between 0.085 and 0.090 $m^3 m^{-3}$. As the prescribed rooting depth of the 3-layer soil

model is the same for C3 crops and grasslands (1.5 m), the resulting MaxAWC varies little. It must be noted that more recent pedotransfer functions (e.g. Wösten et al., 1999, or Saxton and Rawls, 2006) allow much more variability of FC-WP.

The INRA MaxAWC estimates for grassland sites are lower than for C3 crop sites, especially for the average and maximum categories (about 30 mm less). All the MaxAWC estimates obtained in this study are in the range of INRA categories:

- from minimum to average for grasslands,
- from average to maximum for cereals,
- close to maximum for forage pea.

The below average grassland MaxAWC can be explained by the fact that the more productive soils are generally used for crops, and the less productive soils for forests or for grazing and hay production. The high value obtained for forage pea is not out of range, but this result has to be considered with caution (see Sect. 4.3).

Finally, an attempt was made to compare the optimized MaxAWC values with the INRA estimates, but no significant correlations were found.

5 Conclusions

French annual agricultural statistics were used to assess to what extent the ISBA-A-gs land surface model is able to reproduce the interannual variability of the dry matter yield, over the 1994–2008 period. It was shown that, even if ISBA-A-gs does not simulate specific processes related to agricultural practices, the agricultural statistics have potential to evaluate the impact of key model parameters, in particular those related to the plant response to drought. Two parameters impact more markedly the simulations: g_m and MaxAWC. The latter has more influence than g_m and impacts both the amplitude of the interannual variability and the biomass production trend in response to the warming trend observed during the growing period (April–June). It is confirmed that the drought-avoiding and drought-tolerant responses used in SURFEX for C3 crops and grasslands, respectively, provide the best correlations of the simulated above-ground biomass with the agricultural statistics. However, the model could probably be improved by representing managed grasslands (a simple methods based on a LAI threshold was used in this study), and by better mapping MaxAWC. Currently, MaxAWC does not vary much in SURFEX and this study shows that MaxAWC tends to be underestimated for crops, and overestimated for grasslands. These results show the potential of using agricultural statistics for model benchmarking.

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Table 1. Standard values of ISBA-A-gs parameters (Gibelin et al., 2006) for 2 vegetation types (C3 crops and C3 grasslands). The mesophyll conductance in well-watered conditions, g_m, is in units of $\mathrm{mm\,s^{-1}}$, g_c is the cuticular conductance, in $\mathrm{mm\,s^{-1}}$, θ_C is the critical extractable soil moisture content, dimensionless, τ_M is the maximum leaf span time, in days, $\mathrm{LAI_{min}}$ is the minimum leaf area index, in $\mathrm{m^2\,m^{-2}}$, N_L is the leaf nitrogen concentration in % of dry mass, e is the SLA (specific leaf area) sensitivity to N_L, in $\mathrm{m^2\,kg^{-1}\,\%^{-1}}$, f is SLA at $N_L = 0\,\%$, in $\mathrm{m^2\,kg^{-1}}$.

Vegetation Type	g_m	g_c	θ_C	Response to drought	τ_M	$\mathrm{LAI_{min}}$	N_L	e	f
C3 crops	1	0.25	0.3	Avoiding	150	0.3	1.3	3.79	9.84
C3 grasslands	1	0.25	0.3	Tolerant	150	0.3	1.3	5.56	6.73

Table 2. Optimal mesophyll conductance (g_m) and MaxAWC derived from agricultural statistics (Agreste and, in the case of grasslands, ISOP) for four vegetation types: cereals and forage pea (C3 crops) and managed (regular cuts) and unmanaged permanent grasslands. The results are given for the default response to drought of Table 1, and for the alternative response.

Crops	Cereals (wheat, rye, barley, oat, triticale)		Forage pea		Permanent grasslands					
Number of sites	45				48					
Reference time series	AGRESTE				AGRESTE			ISOP		
Management	No	No	No	No	No	Regular cuts	Regular cuts	No	Regular cuts	Regular cuts
Response to drought	Avoiding	Tolerant	Avoiding	Tolerant	Tolerant	Tolerant	Avoiding	Tolerant	Tolerant	Avoiding
Median and stdev of optimal g_m (mm s^{-1}) (*)	1.00 ±0.45	1.75 ±0.49	1.50 ±0.48	0.50 ±0.00	0.75 ±0.43	1.25 ±0.45	0.50 ±0.41	0.75 ±0.46	1.25 ±0.30	0.50 ±0.30
Median and stdev of optimal MaxAWC (mm) (*)	175 ±51	150 ±53	200 ±46	150 ±14	100 ±62	125 ±54	175 ±69	100 ±59	100 ±48	150 ±69
Number of sites where optimal MaxAWC and g_m give significant positive correlations: 1 % level – 0.1 % level	13–2	6–0	20–5	3–1	31–18	43–36	32–13	43–35	47–44	41–27
As above except for median MaxAWC and median g_m	4–1	3–0	10–2	3–1	16–4	30–14	13–5	31–13	44–35	17–7
As above except for optimal MaxAWC with median g_m	9–2	5–0	15–2	3–1	27–9	35–18	21–9	38–27	46–39	33–19
As above except for optimal g_m with median MaxAWC	4–1	3–0	11–3	3–1	20–6	32–16	15–6	30–15	45–37	16–7
Impact on mean R^2 of using median g_m and median MaxAWC (*)	−0.19	−0.11	−0.14	−0.02	−0.18	−0.20	−0.22	−0.16	−0.12	−0.24
Impact on mean R^2 of using median g_m with optimal MaxAWC (*)	−0.08	−0.01	−0.07	−0.00	−0.08	−0.15	−0.12	−0.08	−0.08	−0.10
Impact on mean R^2 of using median MaxAWC with optimal g_m (*)	−0.17	−0.10	−0.13	−0.02	−0.13	−0.17	−0.19	−0.16	−0.11	−0.27

The default response to drought is in bold characters. Note that for cereals, significant negative correlations are found for 6 sites in northeastern France (02-Aisne, 18-Cher, 39-Jura, 51-Marne, 55-Meuse, 60-Oise), and only 1 site (02-Aisne) for forage pea.

[*] Only the sites where optimal gm and MaxAWC give significant correlations at 1 % level are used. The 1 % and 0.1 % levels correspond to $R^2 > 0.41$ and 0.57, respectively.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. Scores for pooled grassland biomass production values (720 values, i.e. 48 administrative units ×15 yr) from AGRESTE and ISOP-STICS, of the unmanaged and managed options of the ISBA-A-gs model: squared correlation coefficient (r^2), root mean square difference (RMSD), standard deviation of differences (SDD), and mean bias (model minus reference data).

Grassland model option	Reference data source	r^2	RMSD (kg m^{-2})	SDD (kg m^{-2})	Mean bias (kg m^{-2})
Unmanaged	AGRESTE	0.70	0.30	0.25	0.17
	ISOP-STICS	0.47	0.25	0.24	0.07
Managed	AGRESTE	0.37	0.22	0.20	–0.08
	ISOP-STICS	0.45	0.29	0.17	–0.23

Table 4. Summary of median MaxAWC estimates, and standard deviations, derived from this study (significant correlations at the 1 % level in Table 2), currently used in the three-layer force-restore (3L) version of ISBA in SURFEX, and the MaxAWC range as estimated using the INRA soil map.

Vegetation Type	Number of sites in France	This study MaxAWC (mm)	SURFEX 3L MaxAWC (mm)	INRA MaxAWC (mm)		
				minimum	average	maximum
Cereals	13	175 ± 51	129 ± 8	93 ± 38	150 ± 42	195 ± 53
Forage pea	20	200 ± 46	129 ± 5	94 ± 30	151 ± 47	208 ± 49
Managed grasslands	47	100 ± 48	129 ± 3	85 ± 41	123 ± 48	170 ± 55

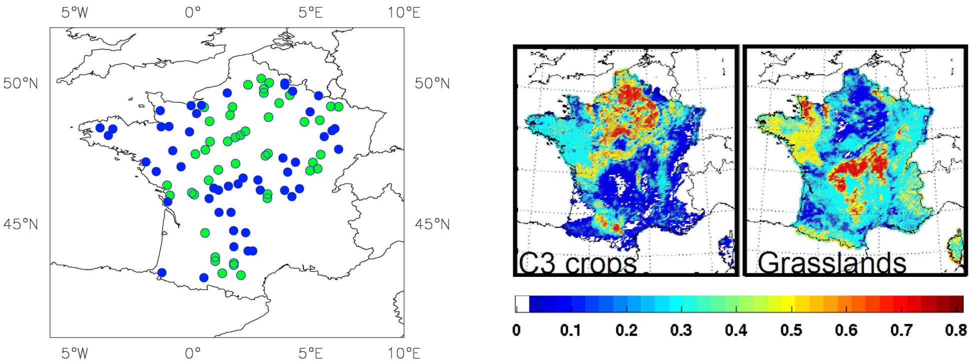


Fig. 1. Studied C3 crops and grassland French sites: (left) SAFRAN grid cells presenting more than 45 % of (green dots) C3 crops and of (blue dots) grasslands, below 1000 m a.s.l., consistent with (right) the fractions of vegetation types derived from ECOCLIMAP-II.

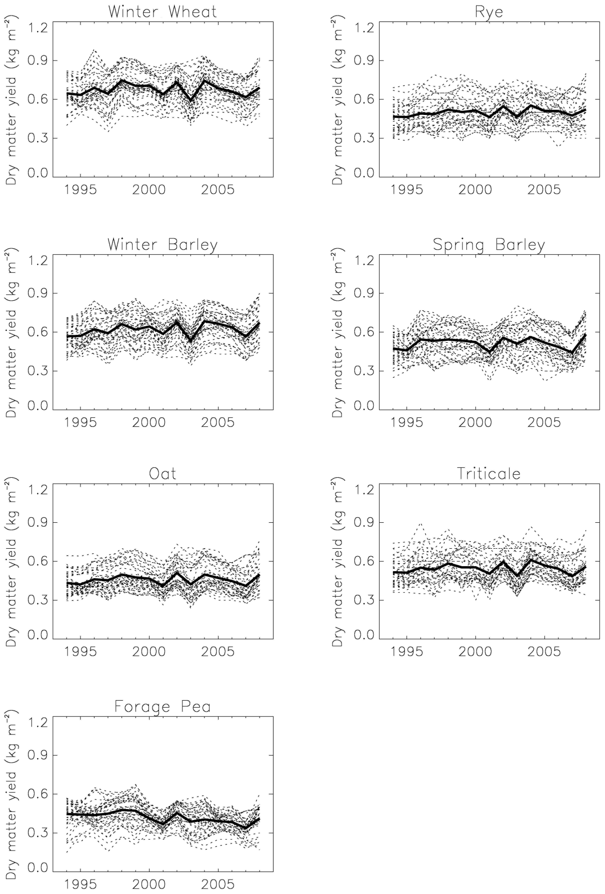


Fig. 2. Agreste (2011) crop yield statistics for 45 “département” administrative units (dashed lines) for cereals (winter wheat, rye, winter barley, spring barley, oat, triticale) and forage pea, from 1994 to 2008. The average trend is indicated (solid line).

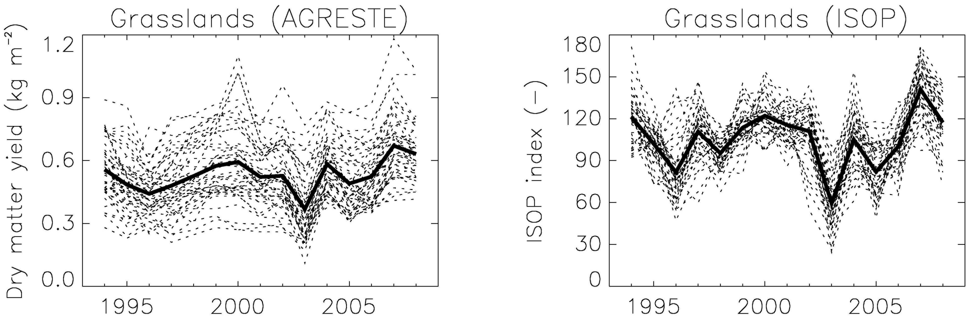


Fig. 3. Agreste (2011) and ISOP grassland production statistics for 48 "département" administrative units (dashed lines), from 1994 to 2008. The average trend is indicated (solid line).

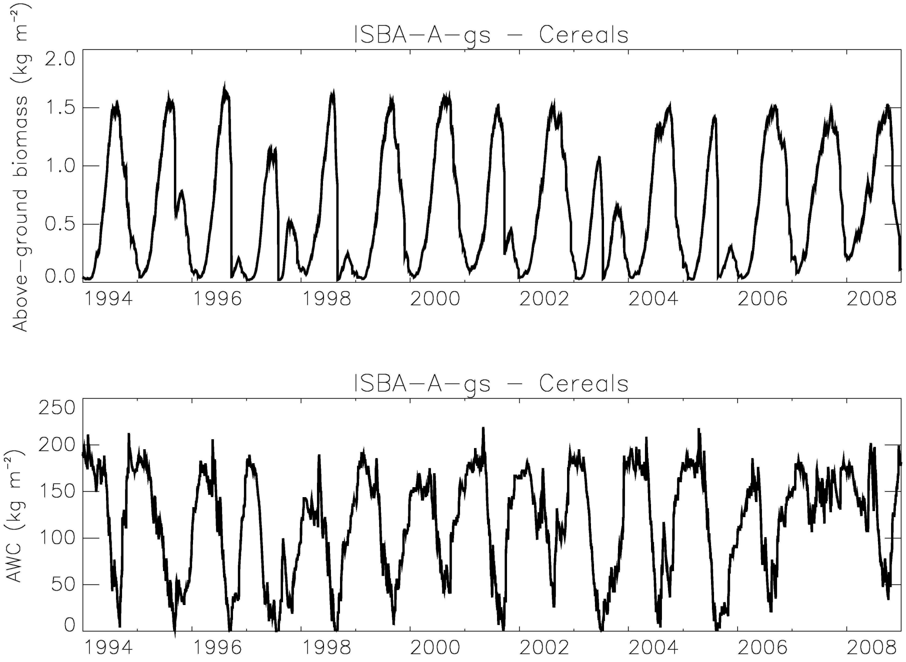


Fig. 4. ISBA-A-gs simulation of C3 crop (top) B_{ag} and (bottom) available soil water content (AWC), for the 1994–2008 period, for the Puy-de-Dôme administrative unit.

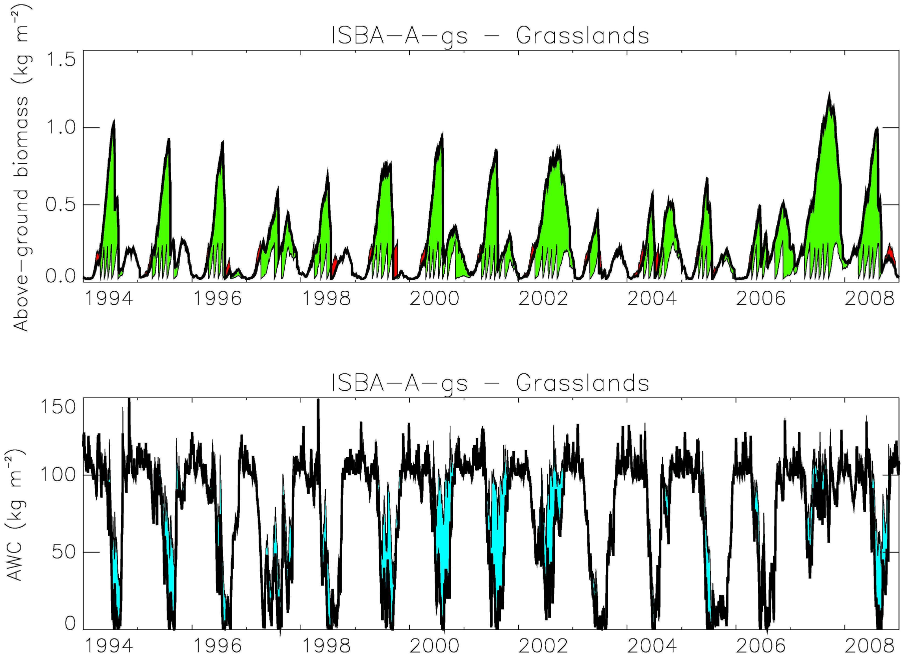


Fig. 5. ISBA-A-gs simulation of managed and unmanaged grassland (top) B_{ag} and (bottom) AWC, for the 1994–2008 period, for the Puy-de-Dôme administrative unit. Higher and lower biomass values for unmanaged grasslands (with respect to managed grasslands) are in green and in red, respectively. Lower AWC values for unmanaged grasslands (with respect to managed grasslands) are in blue.

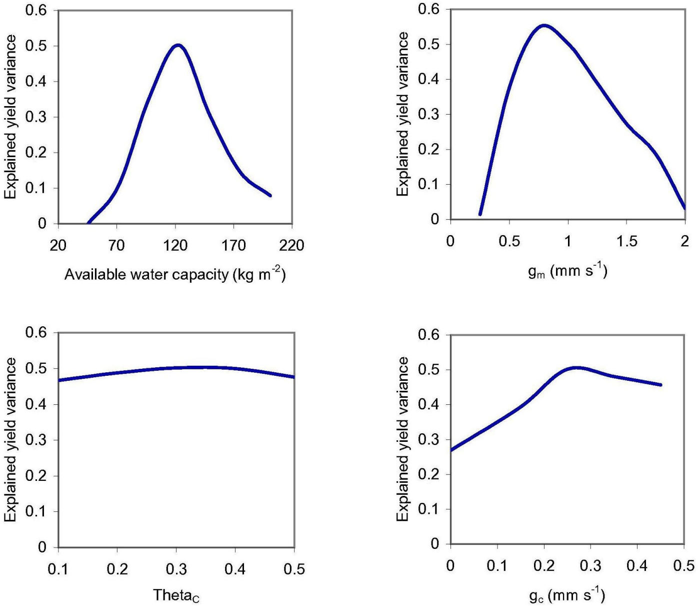


Fig. 6. Impact of ISBA-A-gs parameters on the explained yield variance (R^2) of the simulated annual maximum B_{ag}, for rye in Haute-Garonne, from 1994 to 2008. From left to right and top to bottom: MaxAWC, mesophyll conductance in well-watered conditions, g_m, cuticular conductance, g_c, critical extractable soil moisture content, θ_C.

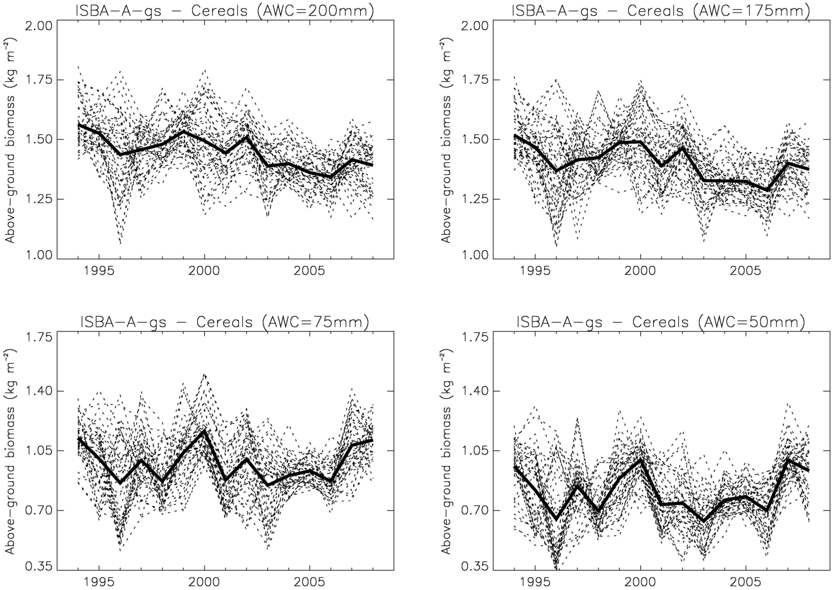


Fig. 7. Impact of MaxAWC on the interannual variability of the annual maximum B_{ag} simulated by ISBA-A-gs, using the median optimal g_m value $g_m = 1\,\mathrm{mm\,s^{-1}}$ found for cereals (Table 2).

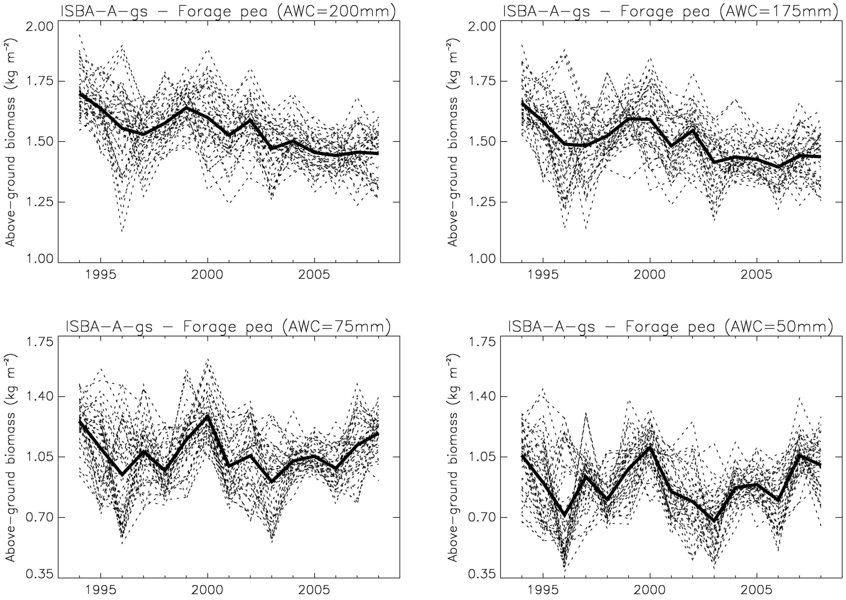
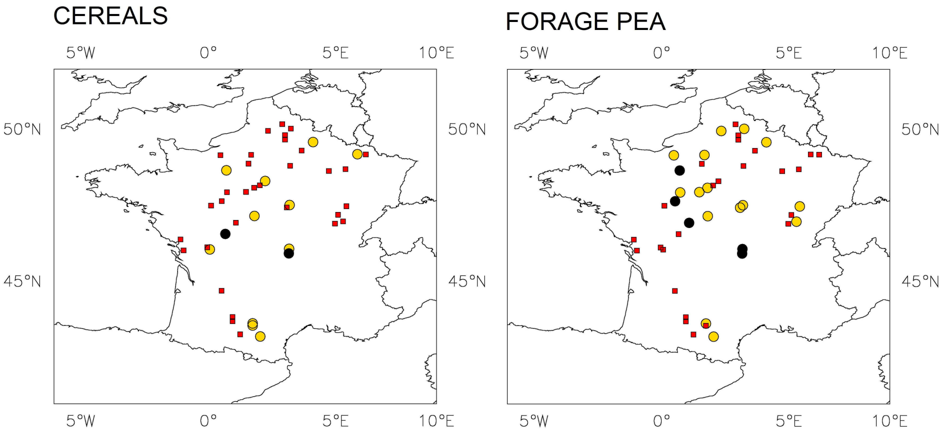


Fig. 8. As in Fig. 7, except for $g_m = 1.5\,\mathrm{mm\,s^{-1}}$ and forage pea.

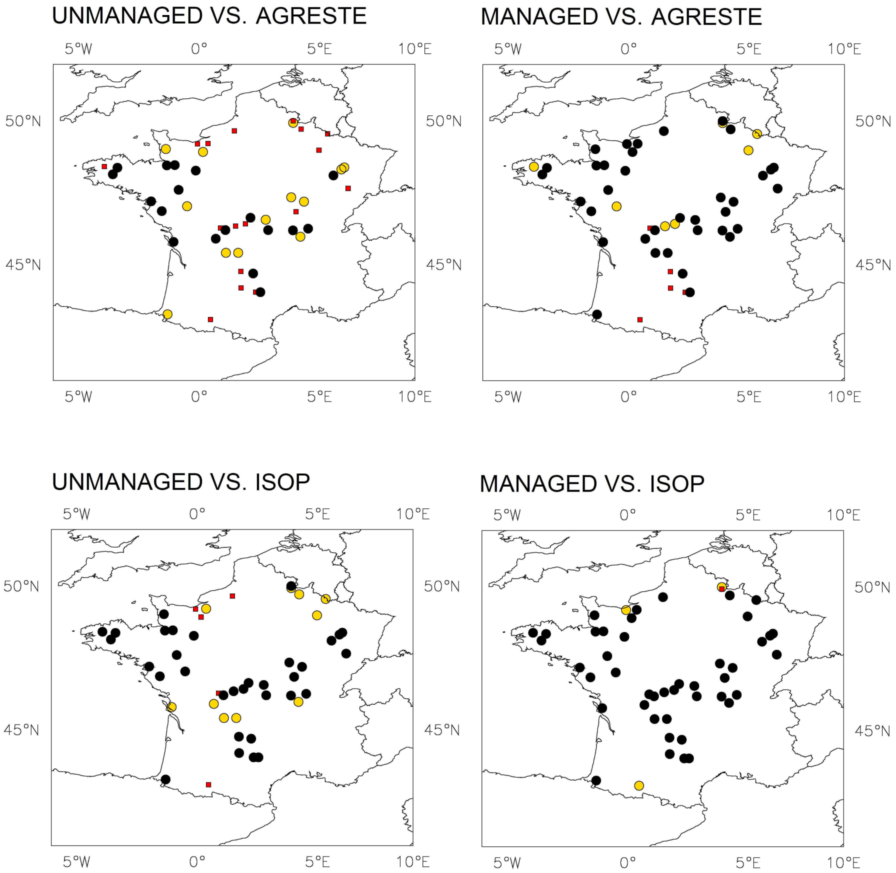


CEREALS

FORAGE PEA

Fig. 9. Best correlation levels obtained for C3 crops using the Agreste data for (left) cereals, and (right) forage pea. Non-significant, significant at the 1 % level, and significant at the 0.1 % level scores are indicated (red squares, yellow dots, and black dots, respectively).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion


UNMANAGED VS. AGRESTE

MANAGED VS. AGRESTE

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Fig. 10. As in Fig. 9, except for unmanaged and managed grasslands, and Agreste and ISOP data.

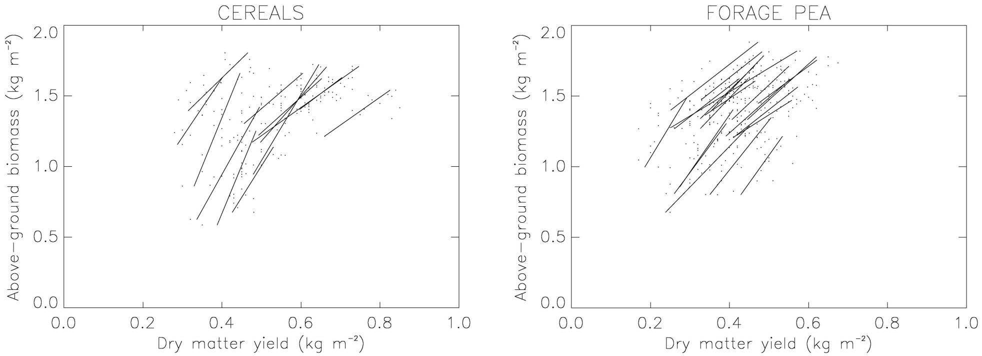

Fig. 11. Simulated annual maximum B_{ag} vs. the Agreste dry matter yields for the sites where a significant correlation (1 % level) is achieved: (left) cereals, (right) forage pea. The drought-avoiding option is used in the ISBA-A-gs simulations. One regression line is plotted by site, and the dots corresponds to the yearly values for all the sites.

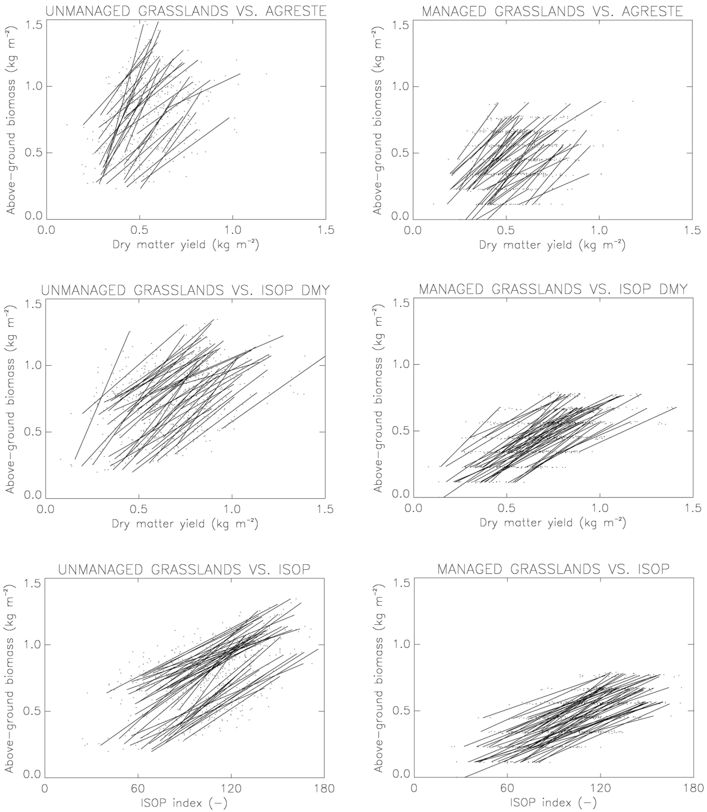

Fig. 12. Simulated (left) cumulated cut biomass of managed grasslands and (right) annual maximum B_{ag} of unmanaged grasslands vs. (from top to bottom) the Agreste dry matter yields, the ISOP STICS dry matter yield, and the ISOP index, for the sites where a significant correlation (1 % level) is achieved. The drought-tolerant option is used in the ISBA-A-gs simulations. One regression line is plotted by site, and the dots corresponds to the yearly values for all the sites.