

# Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data

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Received: 16 September 2010 / Accepted: 16 November 2011 / Published online: 10 December 2011  
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**Abstract** Extreme weather conditions can strongly affect agricultural production, with negative impacts that can at times be detected at regional scales. In France, crop yields were greatly influenced by drought and heat stress in 2003 and by extremely wet conditions in 2007. Reported regional maize and wheat yields were historically low in 2003; in 2007 wheat yields were lower and maize yields higher than long-term averages. An analysis with a spatial version (10×10 km) of the EPIC crop model was tested with regards to regional crop yield anomalies of wheat and maize resulting from extreme weather events in France in 2003 and 2007, by comparing simulated results against reported regional crops statistics, as well as using remotely sensed soil moisture data. Causal relations between soil moisture and crop yields were specifically analyzed. Remotely sensed (AMSR-E) JJA soil moisture correlated significantly with reported regional crop yield for 2002–2007. The spatial correlation between JJA soil moisture and wheat yield anomalies was positive in dry 2003 and negative in wet 2007. Biweekly soil moisture data correlated positively with wheat yield anomalies from the first half of June until the second half of July in 2003. In 2007, the relation was negative the first half of June until the second half of August. EPIC reproduced observed soil dynamics well, and it reproduced the negative wheat and maize yield

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anomalies of the 2003 heat wave and drought, as well as the positive maize yield anomalies in wet 2007. However, it did not reproduce the negative wheat yield anomalies due to excessive rains and wetness in 2007. Results indicated that EPIC, in line with other crop models widely used at regional level in climate change studies, is capable of capturing the negative impacts of droughts on crop yields, while it fails to reproduce negative impacts of heavy rain and excessively wet conditions on wheat yield, due to poor representations of critical factors affecting plant growth and management. Given that extreme weather events are expected to increase in frequency and perhaps severity in coming decades, improved model representation of crop damage due to extreme events is warranted in order to better quantify future climate change impacts and inform appropriate adaptation responses.

## 1 Introduction

Extreme weather events can affect agricultural production significantly, for instance heat waves and droughts (Ciais et al. 2005 and van der Velde et al. 2010), hail storms (Sanchez et al. 1996), excessive cold, and heavy and prolonged precipitation (Rosenzweig et al. 2002).

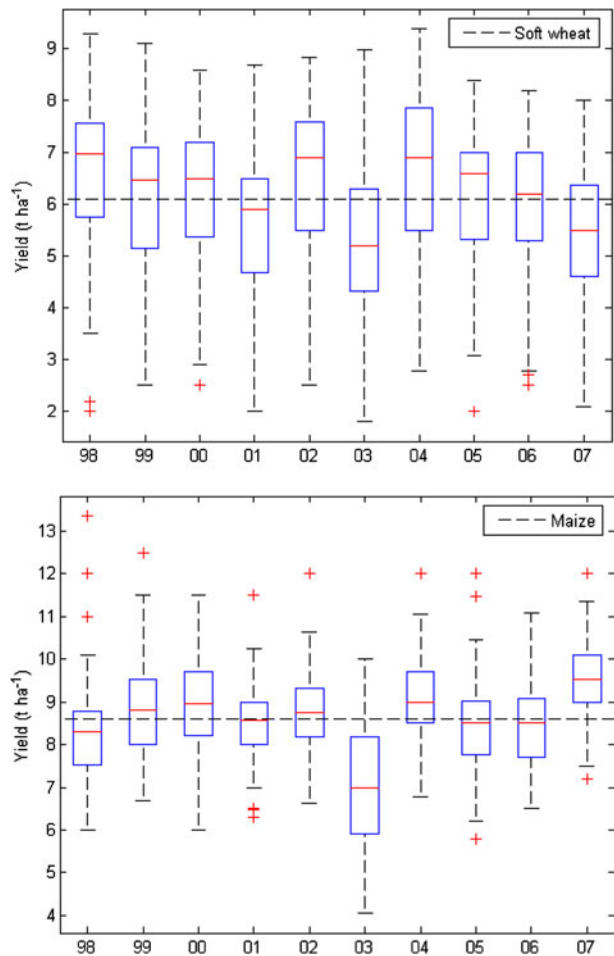
The diverse nature of extreme events leads to variable effects on different aspects of the crop growth cycle and associated field management. Extreme weather events can in fact impact crops both via negative impacts on plant physiological processes and direct physical damage, as well as by affecting the timing and conditions of field operations. For instance, above-threshold temperatures and precipitation lows, leading to heat and drought stress, can negatively affect crop photosynthesis and transpiration (Wolf et al. 1996 and Porter and Semenov 2005), as well as increased pest and disease incidence; and extreme temperature events may also hinder fruit setting and development, critically lowering yield potential (Tubiello et al. 2007). On the other hand, heavy rain, hail storms and flooding lead to crop failures by physically damaging crop canopies, or via anoxic soil conditions limiting root and plant function. Extremely wet conditions can also delay key field operations such as planting and harvesting.

Importantly, the same extreme event can have very different outcomes depending on the time of the year and the crop development stage. Understanding how extreme events modify processes and interactions in agricultural production systems is therefore essential to devising appropriate management responses under currently and future climate regimes. Indeed, future climate change conditions are likely to be characterized by increased frequency of extreme events and thus larger negative impacts on crop yields (Easterling et al. 2007). Therefore, planning for appropriate adaptation responses requires better knowledge of potential damage. This includes improved crop models that better capture dynamics of extreme events (Tubiello et al. 2007), as well as analysis of past information, which can help to: i) Better understand impact dynamics on specific crops and events; and ii) Test and improve the performance of regional crop growth simulation models (CM) against factors and processes influenced by extreme weather events. In France, crop yields were strongly affected by drought and heat stress in 2003 and by extremely wet conditions in 2007. In 2003, below-average spring and summer precipitation was accompanied by high summer temperatures (Loew et al. 2009). By contrast in 2007, France's North-western and Central regions experienced above average summer precipitation, with localized intense rain storms.

Reported maize and wheat yields were historically low in 2003, in contrast to 2007 when wheat yields were lower and maize yields were higher than long-term averages (Fig. 1).

The 2003 heat wave and drought was exceptional, generating an overall loss of € 4 billion to the agricultural sector in France (Copa-Cogeca 2003). It was estimated that over three quarters of the soft wheat output and some 55% of the maize output lost at European Union level were attributable to the heat wave in France (Copa-Cogeca 2003). France

**Fig. 1** Boxplots of reported regional (NUTS3) wheat (top) and maize (bottom) yields ( $\text{t ha}^{-1}$ ) in France from 1998 to 2007. On each box, the central mark is the median, the edges of the box are the lower quartile and upper quartile values, the whiskers extend to 1.5 times the interquartile range away from the top or bottom of the box. Outliers are indicated by red plus symbols



produced 29 MT of wheat in 2003, 21.5% down compared to 2002 and France's maize output equalled 11.5 MT, 30% down compared to 2002 (Agra Europe 2003).

By contrast, extreme events in France in 2007 were characterized by very high precipitation, leading to excessive soil moisture in the summer, favouring pest and disease development and increasing lodging with a high impact on straw cereals (Mars Bulletin 2007). The excessive and persistent rain hindered field accessibility and work, affecting wheat harvest, while also reducing grain quality and generally leading to low wheat yields. Temporary flooding occurred locally and harvests were delayed or made under unfavourably wet conditions. Poor harvests and a failure to meet milling specification in France and Germany had adverse impacts on farm gate grain prices (NABIM 2007). By contrast, the 2007 events did not affect maize productivity. In fact, dry conditions that finally set in at the beginning of September 2007, coupled to the very good soil moisture availability from the excess summer rain, lead to very favourable conditions for maize –which in France is not harvested until mid-October (Mars Bulletin 2007).

While the general reason for the different impacts of extreme events on crop yields in France in 2003 and 2007 and between crop species is thus fairly well understood, crop

models have not been tested to date against these specific conditions. To capture the complexity of damage resulting from extreme events with models, fine-resolution observations and/or data-model fusion approaches (including use of high-resolution remote sensing) can give the best indication of spatial variability at field level (see e.g. Zaitchik et al. 2006). Nevertheless, it is clear that certain factors triggered by extreme events can have aggregate responses that are captured in regional crop production statistics. These coarsely aggregated data can, and should be used, to evaluate and possibly improve performance of large-scale crop models to make them better suited in representing extreme conditions. Especially since the use of crop models for large scale simulations under climate change is increasing (IPCC, WGII, AR4 Ch5: Easterling et al. 2007).

We therefore decided to test EPIC—one of the most widely used crop models in Europe and worldwide. Besides crop modelling, we use remotely sensed soil moisture to assess the impacts of both extremely dry and extremely wet events on regional crop productivity in France, mediated via effects on soil moisture conditions. Specific objectives were:

1. Analyse the spatial variation in yield anomalies in 2003 and 2007 for wheat and maize in France;
2. Investigate the statistical relation between remotely sensed soil moisture observations and crop yields at regional scale;
3. Test the performance of a spatial implementation of the EPIC crop model (Williams 1995; Bouraoui and Aloe 2007) in capturing key causal relations between rainfall, soil moisture, and crop yields.

## 2 Materials and methods

### 2.1 Data sources

Annual yield data of wheat and maize for the period 1989–2006 at provincial administrative level (NUTS3) for France were obtained from AGRESTE (<http://www.agreste.agriculture.gouv.fr>). Absolute annual yield anomalies were calculated with respect to the average provincial yield over the period 1998–2007.

The remotely sensed soil moisture products derived from the Advanced Microwave Scanning Radiometer (AMSR-E) on the Aqua satellite as included in the historical climatology of satellite-derived global land surface moisture presented by Owe et al. (2008) are used here. Remotely sensed soil moisture can be used to evaluate soil moisture modelled by regional crop models; especially since the retrieval of remotely sensed soil moisture is well-suited for herbaceous vegetation cover in regions with little relief, characteristic of cropland (e.g., Rudiger et al. 2009). Volumetric soil moisture was retrieved from the passive microwave observations using a recently developed approach which is based on the microwave polarization difference index (Owe et al. 2008). Passive microwave measurements are sensitive to soil moisture in the top 1–1.5 cm of the soil, but compared well with in-situ ground measurements at 5-cm (Owe et al. 2008). Owe et al. (2008) observe that satellite observations are highly sensitive to soil moisture changes at the surface (for example precipitation events), but that these changes are also reflected in deeper ground measurements. At greater depths there may be a delay and a change of magnitude. In accordance with Loew et al. (2009) we selected the less noisy daytime ascending passes. The footprint dimensions associated with the used frequency of 6.9 GHz equals approximately 74×43 km.

Rudiger et al. (2009) showed that this AMSR-E soil moisture product shows a good relation with in-situ measured soil moisture (0–6 cm) in south-western France, remotely sensed soil moisture from ERS-Scat, and modelled soil moisture from a coupled land surface model over France. Remotely sensed soil moisture has been used for crop yield prediction using data assimilation (de Wit and van Diepen 2007).

The products described in Owe et al. (2008) were provided as 0.25° grid cells. These daily soil moisture data were processed to obtain 15-day observations averaged over each region (NUTS3) from the second half of June 2002 until the end of 2007. This was done by first deriving 15-day median values per pixel to obtain representative values. Subsequently, a moving Savitzky-Golay filter with a frame size of 7 data points (4th-order polynomial) for temporal smoothing (Savitzky and Golay 1964) was applied. The smoothed 15-day soil moisture was averaged at regional level (NUTS3) in line with the reported yield data. Two types of soil moisture anomalies were calculated: the difference in absolute moisture content (% ,  $\text{cm}^3 \text{cm}^{-3}$ ) with respect to averages over the complete measurements period; and standardized anomalies with respect to the standard deviation observed in that region so that (following Grumm and Hart 2001):

$$N_i = \left( \frac{SM_i - SM_{\mu,i}}{\sigma_i} \right) \quad (1)$$

where  $SM_i$  is the observed soil moisture,  $SM_{\mu,i}$  is the mean soil moisture, and  $\sigma_i$  is the standard deviation for region  $i$ . The magnitude of the anomaly is given by  $N$ . Soil moisture anomalies were calculated over for the 15-day periods, for the individual months June, July and August, and for the summer season (JJA).

## 2.2 EPIC crop model and inputs

EPIC (Environmental Policy Integrated Climate; previously Erosion Productivity Impact Calculator) is a biophysically based crop model (Williams 1995). We use herein the spatial EPIC geo-database environment developed and tested for major crops in Europe (Bouraoui and Aloe 2007; van der Velde et al. 2012). The system was used for an assessment of the role of irrigation in reducing the drought impact on maize yield during the 2003 heat wave in France (van der Velde et al. 2010).

Growth-defining factors determining potential crop production in EPIC include radiation, temperature and  $\text{CO}_2$  concentration. Biomass is calculated from conversion of intercepted photosynthetic active radiation using a radiation use efficiency factor. Crop yield is calculated via a harvest index, determining yield as a fraction of above-ground biomass. Actual biomass is a function of potential biomass which is reduced by growth constraints due to water, temperature, or aeration stress. In the simulations presented herein all plant nutrient requirements were assumed satisfied, i.e., no nutrient stress was simulated. Crop growth simulations were performed for rainfed wheat, and rainfed and irrigated maize with a maximum application of  $60 \text{ mm day}^{-1}$  and a weekly irrigation interval (see van der Velde et al. 2010).

The phenomenological development of crops is based on daily heat units accumulation. The model uses thermal time to compute date of anthesis and flowering, harvest maturity, as well as affecting physiological processes such as leaf senescence, leaf area growth, root depth, crop height and partitioning of biomass among roots, shoots, and grain. Root zone soil moisture (RZSW, [mm]) is calculated as the amount of available water above wilting point. The total number of heat units required to bring the crop to maturity was calculated

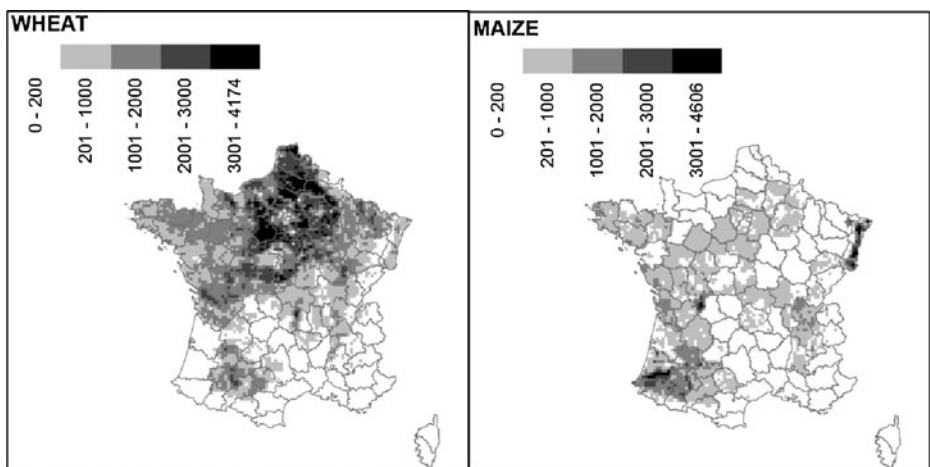
using regional long term minimum and maximum temperatures, and optimum and minimum crop growth temperatures for cultivars appropriate for France, and the average number of days for the crop to reach maturity (Cabelguenne et al. 1999). Planting dates were taken from the JRC-MARS Crop Growth Monitoring System.

This EPIC implementation runs with a daily time step on  $10 \times 10$  km grid, with each cell representing specific soil, meteorological, and topographic attributes. Daily meteorological data were obtained from the Joint Research Centre's (JRC) MARS meteorological database, given on a  $50 \times 50$  km grid. Land use information was taken from a European land use map developed at JRC that combines land cover data of CORINE 2000 with regional crop areas taken from the European farm structure survey statistics—thus adding crop specific information to the CORINE agricultural land use classes while respecting regional crop areas (Fig. 2). Digital terrain information was derived from the 90-m resolution SRTM (Shuttle Radar Topographic Mission) digital elevation model. Soil data were obtained from the European Soil Bureau Database (ESBD 2.0). The spatial data were linked to the  $10 \times 10$  km modelling grid. Each  $50 \times 50$  km grid cell of the meteorological database was linked to twenty-five  $10 \times 10$  km grid cells. Crop areas defined in the European land use map were tabulated with a class aggregation for each  $10 \times 10$  km grid cell by crop category. Soil data originally at  $1 \times 1$  km were aggregated to the modelling grid (see Bouraoui and Aloe 2007 and references therein).

### 3 Results

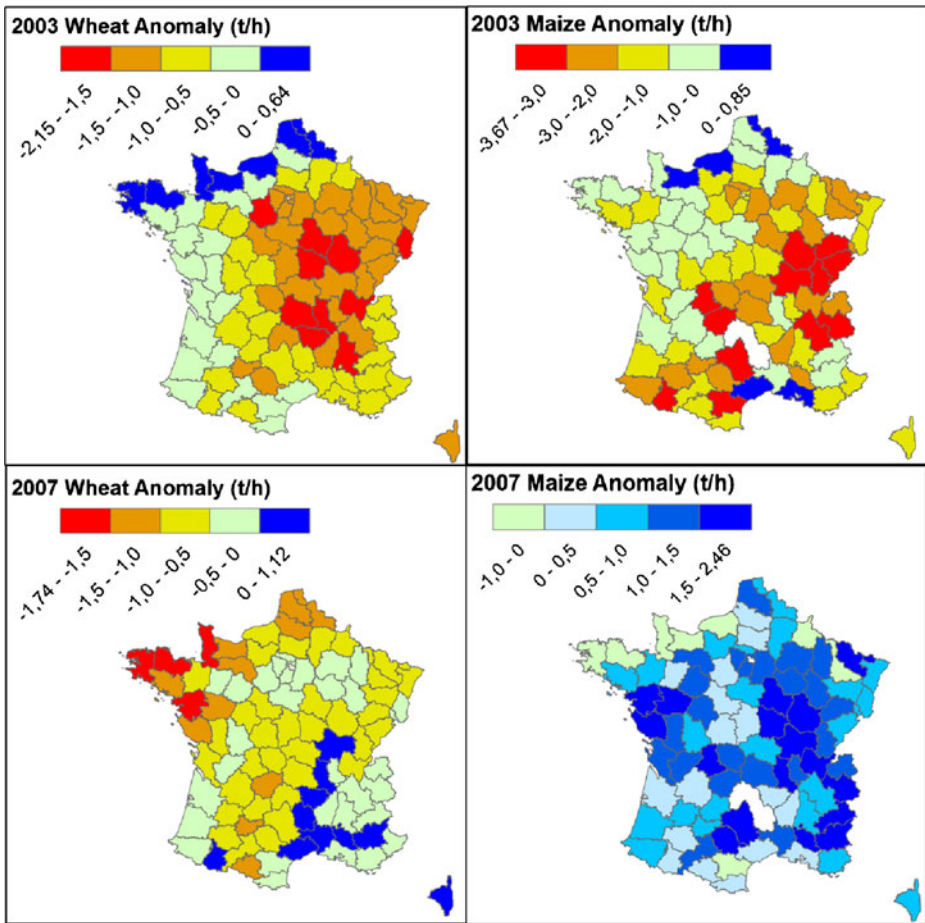
#### 3.1 Statistical data

The 2003 heat wave strongly affected yields of wheat and maize throughout France (Fig. 3). The highest regional wheat yield losses ( $>1.5 \text{ t ha}^{-1}$ ) clustered in the heat wave impacted east of France. Wheat yields were not particularly affected in the regions bordering the cooler and wetter Atlantic coastal zone. Reductions in regional maize yield (a combination



**Fig. 2** Wheat and maize crop areas (ha) at the 10 km (10,000 ha) model grid. Regions (NUTS3) are indicated





**Fig. 3** Absolute wheat and maize yield anomalies ( $\text{t ha}^{-1}$ ) for 2003 and 2007 compared to the 1998–2007 average over France at regional level (NUTS3). Minimum and maximum crop yield anomalies are indicated in the legend. Red and green colours indicate negative anomalies while blue colours indicate positive anomalies, white indicates missing data

of rainfed and irrigated maize) in 2003 ( $>2 \text{ t ha}^{-1}$ ) were also pronounced. Van der Velde et al. (2010) showed that—unlike wheat, which is largely rainfed—the negative impacts on maize depended on the fraction of irrigated maize—especially in the climatic transition zone between 44 and 48° latitude. In these regions maize losses were limited thanks to irrigation applications, with the additional water partly compensating for drought and heat stress (van der Velde et al. 2010).

Impacts on wheat and maize yields were more diverse following a wetter than average growing season in 2007. Lower than average wheat yields occurred throughout France in 2007, with the North-western regions most strongly impacted, with recorded losses  $>1.5 \text{ t ha}^{-1}$ . A few regions in the south however had higher yields than normal. Maize yields were low in parts of Normandy and Brittany, but above average in most of France and particularly high ( $>1.5 \text{ t ha}^{-1}$  above average) in the east (Fig. 3).

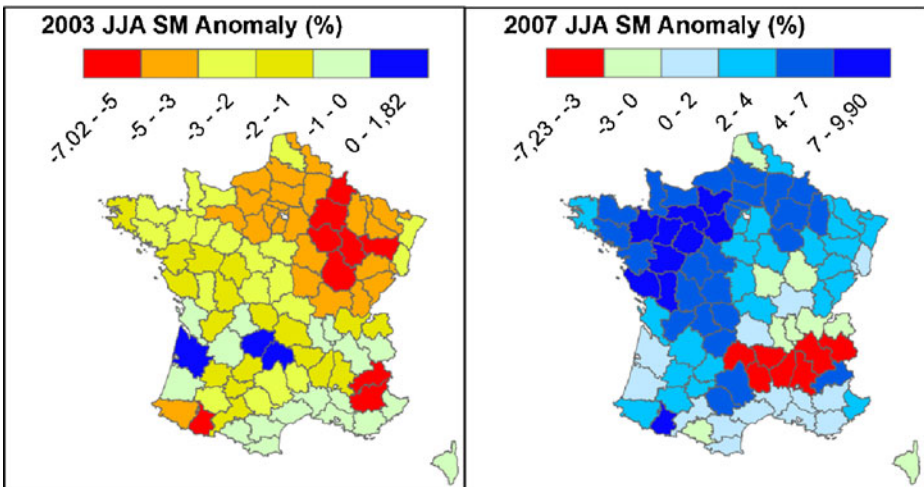
### 3.2 Remote sensing data

Analyses of the seasonal summer (JJA) soil moisture anomalies were consistent with the reported yield anomalies in 2003 and 2007 (Fig. 4). They showed that in 2003, these were below average for most regions in France, and particularly in the North-eastern part of the country. In 2007, by contrast, soil moisture anomalies indicated North-western France to be particularly wet, while South-eastern France remained drier.

The relation between standardized seasonal summer (JJA) soil moisture anomalies and regional yield anomalies for 2002–2007 are shown in Fig. 5. A clear difference in the relation of wheat and maize yield anomalies with soil moisture anomalies was observed in 2007.

In the period of 2002–2006, the overall correlation  $r$  between JJA SM and wheat yield anomalies was 0.39 ( $p < 0.0001$ ). For maize, the relation between JJA soil moisture and maize yield anomaly in 2002–2007 was significant, with an  $r$  of 0.39 ( $p < 0.0001$ ). The spatial correlation between JJA soil moisture and wheat yield anomalies was significant and positive in dry 2003 ( $r = 0.32$ ,  $p$ -value  $< 0.002$ ) and significant and negative in wet 2007 ( $r = -0.35$ ,  $p$ -value  $< 0.001$ ). The spatial correlation between JJA soil moisture and maize yield anomalies was only significant in 2005 ( $r = 0.41$ ,  $p$ -value  $< 0.001$ ). The relation of annual wheat yield with bi-weekly soil moisture anomalies was strongest in 2003 and 2007 (Table 1). In 2003, wheat yield anomaly correlated positively with bi-weekly soil moisture observed during the first 2 weeks of June until the last 2 weeks of July. In 2007, the relation was negative and significant from the first half of June to the first half of August. No significant relations were found between bi-weekly soil moisture and maize yield anomalies.

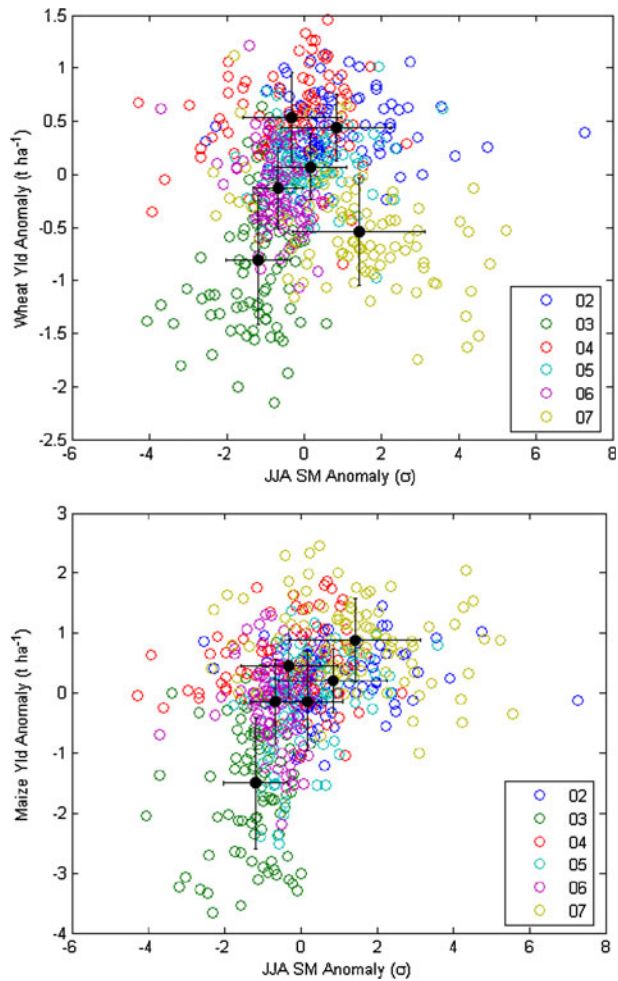
Over France, at regional level, significant relations were found between remotely sensed summer (JJA) soil moisture and modelled root zone soil moisture (Fig. 6). Correlations were highest over regions characterised by a high proportion of low lying cropland areas with little relief and lower over regions with a large share of forests and grasslands generally occurring at higher elevation; confirming Rudiger et al. (2009) observation that retrieval of remotely sensed soil moisture is well-suited for herbaceous vegetation cover in



**Fig. 4** Remotely sensed (AMSR-E) soil moisture anomalies (% absolute moisture content) over France at regional level (NUTS3) for JJA 2003 and JJA 2007. Red and yellow colours indicate negative anomalies while blue colours indicate positive anomalies



**Fig. 5** The relation between AMSR-E remotely sensed standardized summer (JJA) soil moisture anomalies ( $\sigma$ ) and regional wheat (top figure) and maize (bottom figure) yield anomalies ( $t\ ha^{-1}$ ) plus annual averages and standard deviations from 2002–2007



regions with little relief. The good relation between simulated root zone soil moisture and remote sensing data indicate that EPIC captures the soil water dynamics.

### 3.3 Crop simulation data

The EPIC crop model was found to be capable of representing the observed loss in wheat and maize yields in 2003 due to drought and high summer temperatures (Fig. 7, for a discussion on maize yields also see van der Velde et al. 2010). The model simulation of rainfed maize was also able to reproduce the above-average maize yields in 2007, indicating that no negative effects of extreme precipitation were present on the crop. As previously discussed, the onset of dry conditions in September 2007, coupled to good soil water reserves from the summer rains, in fact resulted in very good grain setting, growing and harvesting conditions for this crop. Indeed, reported yields were above average for Maize in 2007. Simulations of irrigated maize indicated average yields of  $\sim 10\ t\ ha^{-1}$  and annual irrigation water use of  $\sim 400\ mm$ .

**Table 1** Correlation coefficients of the relation between absolute 15-day soil moisture anomaly and annual wheat yield anomaly (p-value <0.05<sup>\*</sup>; p-value <0.005<sup>\*\*</sup>; p-value <0.001<sup>\*\*\*</sup>, NA = not available and NS = not significant)

	June (1st half)	June (2nd half)	July (1st half)	July (2nd half)	Aug (1st half)	Aug (2nd half)
2002	NA	NS	NS	NS	NS	NS
2003	0.30**	0.44***	0.42***	0.26*	NS	NS
2004	NS	0.29*	0.32***	NS	NS	-0.36***
2005	NS	NS	NS	NS	NS	NS
2006	NS	-0.37*	-0.43**	-0.30*	NS	NS
2007	-0.28*	-0.29*	-0.41***	-0.38***	-0.20*	NS

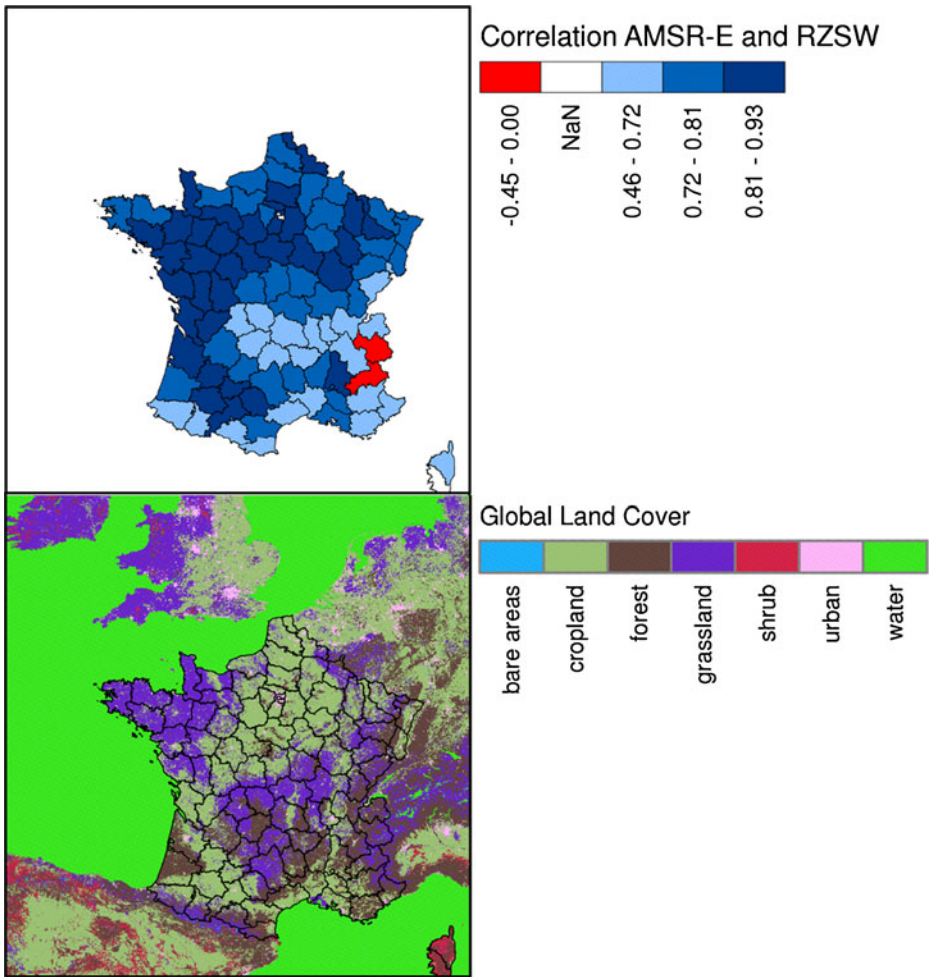
However, EPIC failed to reproduce the case of the 2007 wheat crop, for which, by contrast to maize, severe impacts of extreme wetness conditions were observed. The model instead computed average wheat yields for 2007 (Fig. 7).

#### 4 Discussion

The negative impact on wheat and maize yields observed and simulated in 2003 indeed related to low available root zone soil moisture throughout the season (Fig. 8; shown for wheat yield anomalies). In simulations by EPIC, the negative impacts of heat and drought stress on crop yields were due to soil temperatures higher than the optimal growth temperature and significant reductions in plant transpiration limiting biomass production. Drought stress was generally preceded by heat stress. Conditions were opposite in 2007, with excess precipitation in the summer leading to excess moisture conditions. However, although the model was capable of simulating soil water dynamics in 2007—as shown by comparing simulated results with satellite derived soil moisture information—no negative yield anomalies were simulated. This was in line with maize yields. Indeed, both simulated and reported maize yields were above-average maize yields in 2007, indicating that no negative effects of extreme precipitation were present on the crop. By contrast, negative impacts of extremely wet conditions were reported for 2007 wheat yields—which the model did not capture.

We therefore ran additional simulations of wheat by increasing the response of EPIC to water saturation associated with excessive soil moisture conditions, to test whether the exceptional conditions in 2007 could be captured by increasing the model's sensitivity to this factor. This however resulted in generally lower simulated yields compared to the control run, with no particular additional negative effect on 2007 anomalies. Hence, we concluded that negative impacts on wheat observed in 2007 were the result of factors not included in EPIC.

As discussed, the main precipitation events in 2007 were centred on the harvesting period of wheat. The weaker morphological structure of wheat and its frailer root system (weaker standing power) may have led to lodging under adverse weather conditions such as heavy rain and wind events. Lodging can significantly affect grain formation and lead to harvesting problems and losses. In addition, development of certain harmful pests and diseases such as Septoria leaf blotch (*Mycosphaerella graminicola*) are specifically associated with wet conditions and can lead to significant wheat yield losses (Kristensen et al. 2010). Finally, secondary growth in combination with a flattened crop makes

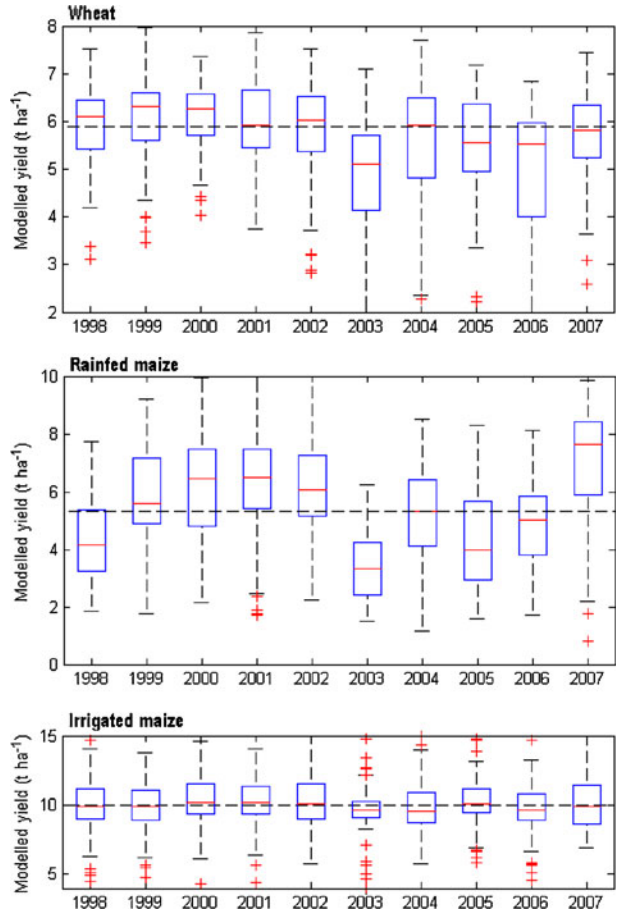


**Fig. 6** Correlations between AMSR-E remotely sensed standardized summer (JJA) soil moisture and EPIC modelled root zone soil moisture (RZSW) from 2002–2007 at regional level (NUTS3) (top) and dominant land cover classes from GLC2000 (bottom)

harvesting difficult and can subsequently lead to poor grain quality and high yield losses. For instance, Landau et al. (2000) found that rainfall in the week preceding harvest negatively affected wheat yield in Britain and attributed this to adverse harvesting conditions.

The EPIC model overestimation of wheat yields in 2007 can therefore be explained to inability to simulate several factors related to excessive wetness conditions. First, lack of representation of negative impacts of wet soil conditions that hamper harvesting operations related to machinery access and operation, delaying harvest. Second, model inability to simulate the impact of excessively wet soils on crop-specific root lodging processes. Thirdly, a possible model underestimate of the impact of excessively wet soils on plant physiological and growth processes (through roots and root-mediated dynamics). Finally, a lack of representation of pest and disease dynamics that become significant under

**Fig. 7** Boxplots of modelled regional wheat (top), rainfed maize (middle), and irrigated maize (bottom) yields ( $\text{t ha}^{-1}$ ) from 1998 to 2007. On each box, the central mark is the median, the edges of the box are the lower quartile and upper quartile values, the whiskers extend to 1.5 times the interquartile range away from the top or bottom of the box. Outliers are indicated by red plus symbols



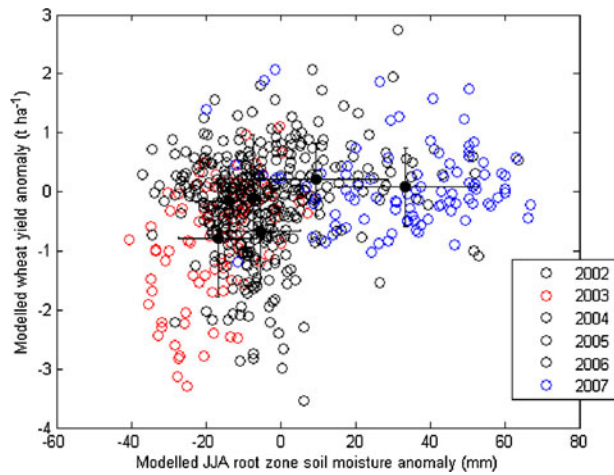
excessively wet conditions and are capable of depressing grain yield. Indeed, the results and discussions in this paper confirm and further quantify existing evidence in the literature, highlighting severe limitations of current leading crop models. In particular, previous analyses with DSSAT models had indicated failure to capture negative yield anomalies under extremely wet conditions, especially under protracted periods of excessive soil moisture (Rosenzweig et al. 2002).

The findings herein focus on high-level data for France, using statistical, remote sensing and simulation analysis to better quantify the impacts of specific dry and wet conditions on crop yield anomalies.

#### 4.1 Relevance for climate change projections

The findings of this paper support and further quantify conclusions of previous work (i.e., Easterling et al. 2007), prescribing caution in the use of leading crop models for the projection of crop productivity anomalies under climate change scenarios with extreme events. They point to the need to improve crop models, so that the impacts of extreme events on crop function and productivity—in particular, increased soil wetness and other effects of heavy precipitation—be better represented in these models.

**Fig. 8** The relation between modelled root zone soil moisture anomalies (mm) and wheat anomalies ( $\text{t ha}^{-1}$ ) plus annual averages and standard deviations from 2002–2007



Our findings also confirmed that current crop models are, by contrast, quite good at capturing negative yield anomalies that are observed under drought conditions. This is because there are strong direct relationships between soil moisture, drought stress and biomass assimilation—which crop models can well reproduce. By contrast, the negative direct and indirect impacts on crop yields of excessive soil moisture and heavy precipitation are more difficult to capture. Indeed, improvements needed include better simulation of root responses, representations of pest and disease outbreaks under wet conditions, as well as better representation of machinery operations affecting indirectly harvest yield. Most crop models in use today for large regional scale simulations, especially for climate change assessment, lack to varying degrees the capability to simulate these critical dynamics. The implication is that current crop simulation results undertaken under particularly “wet” scenarios of climate change are likely to overestimate positive yield impacts, and should be used with caution (Easterling et al. 2007).

For France and Western Europe in general, current indications are for increased frequency of summer droughts of the kind observed in 2003. Regional climate models (RCM) predict that the late 21<sup>st</sup> century climate in France will increasingly be characterized by summertime drought (Raisanen et al. 2004). The simulations by Raisanen et al. (2004) reveal that under both the B2 and A2 scenarios the decrease in soil moisture in France will be greatest in late summer, with corresponding increase in sensible heat flux of about 40%–50% in July and August (also see Seneviratne et al. 2010). Lenderink and van Meijgaard (2008) substantiate increased summer droughts and predict a decrease of 15–60% in 2071–2100 JJA precipitation totals compared to 1971–2000. Changes in projected precipitation intensity and thus impacts on arable agricultural are more uncertain over France. Lenderink and van Meijgaard (2008) predict a relative change of 40–60% in the 99<sup>th</sup> percentile of 1-h precipitation intensity in the North-East of France. Increases in daily rainfall extremes are smaller elsewhere for France (Lenderink and van Meijgaard 2008).

## 5 Conclusion

Using remotely sensed observations of soil moisture, we quantified the contribution of soil moisture to inter-annual variation in reported crop yields at regional level. Wheat yields

were negatively affected both by dry and wet conditions, whereas maize yields only decreased in dry 2003, but increased in wet 2007. Spatial within-year variation in JJA soil moisture was shown to be correlated positively with wheat yield during the heatwave in 2003 and negatively with wet conditions observed in 2007. The EPIC model was capable of capturing the physiological impact of the 2003 heat wave and drought on wheat yields, but did not reproduce the wheat yield loss observed under the wet conditions in 2007. The overestimation of wheat yields in 2007 was discussed in terms of likely model misrepresentation of direct factors, such as key plant growth processes that become important under these conditions (plant lodging, aeration stress, pest and disease development), as well as incapacity to represent indirect factors such as the ability to conduct harvesting operations.

The need to better capture the negative impacts of extreme events on crop yields was clearly highlighted. In order to improve estimates of potential damage to crops, as well as to better assess potential for adaptation under increased frequency of extreme events, current leading crop models should be modified to better simulate impacts of heavy precipitation events, especially those leading to excessive soil moisture conditions.

**Acknowledgments** The spatial EPIC crop model implementation used for this study was developed by the Joint Research Centre of the European Commission. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement nr. 226701 (CARBO-Extreme).

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