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Estimating irrigation use and effects on maize yield during the 2003 heatwave in France☆

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ABSTRACT

The decline in maize yield and production during the 2003 heatwave and associated drought in France was only partly minimized by irrigation. National 2003 maize yield loss equalled ~1.5 t ha^{-1} compared to the 2000–2006 average. Spatially distributed maize irrigated area percentages were calculated earlier (Wriedt et al., 2009a) and correlate negatively to the 2003 yield anomaly between 44.5° and 48° latitude. The percentages are used to weigh irrigated and rainfed simulations with the EPIC crop growth model that runs on a 10 by 10 km grid with relevant land use, terrain, soil and management information. Maize was not irrigated in one simulation while other simulations allowed for daily, weekly and biweekly irrigation with a maximum application of 60 mm day^{-1}. The model reasonably reproduces regionally reported yields from 1999 to 2003. In regions with maize area irrigation percentages >20% yield loss in 2003 was reduced by ~53% relative to regions with maize irrigation percentages <20%. Similarly, simulated yield loss was compensated by irrigation by ~25% with biweekly and by ~42% with weekly irrigation in these regions. Even though yield loss was lower in regions with higher maize irrigation percentages; yield loss was still very considerable. Modelling suggests that regional drought mitigation increased with increasing maize irrigation percentages between 0 and 40%. At higher irrigation percentages the compensating effect of irrigation was small. Although the current irrigation infrastructure is sufficient under normal meteorological conditions, areas without irrigation infrastructure experienced high irrigation requirements during the extreme conditions in 2003. Since increasing the irrigation frequency from two weeks to one week had a significant impact on maize yield in 2003, but not in 2002, the most appropriate difference in irrigation rate is provided by the difference between the biweekly rate in 2002 (484 mm year^{-1}) and the weekly rate in 2003 (743 mm year^{-1}) which equals 259 mm year^{-1}. This corresponds to an increase in irrigation water use of ~1761 million m^3 compared to 2002 (~0.68 million ha of irrigated maize). Adapting to increased frequency of droughts under further climate change will require robust water allocation policies.

1. Introduction

Irrigation is an essential element of agricultural production in Southern Europe. In Northern and Central Europe irrigation is mainly used to improve production in dry summers (Wriedt et al., 2009b). In France these regions are located along a transitional N-S gradient. In France, 10–20% of total annual consumptive water use is used for irrigation, but this can go up to 80% regionally during dry conditions (UNESCO, 2006). Luterbacher et al. (2004) concluded that the summer of 2003 was probably the hottest summer in Europe since 1500 AD. France's agricultural production was strongly affected by the 2003 heatwave. The extremely dry and hot conditions also affected irrigated crops (COPACOGECA, 2003). France's maize output equalled 11.5 Mt, 30% down compared with 2002. It was estimated that 55% of the maize output lost at EU level (compared with 2002) was attributable to the drought in France (COPACOGECA, 2003). The financial loss caused by the drought was estimated at 265 million € for maize alone. An example of the development of weather conditions during the drought period in comparison to the previous years is given in Fig. 1 as daily and cumulative monthly rainfall and maximum temperature in France at 4.7° longitude and 46.8° latitude.

Heatwaves will accelerate crop development and advance ripening and maturity. Fischer et al. (2007a,b) showed that a rainfall deficit in the months preceding the 2003 heatwave combined with an excess in total net radiation in late winter 2002 and spring 2003, contributed to anomalous soil moisture

☆ The statements expressed here are purely those of the author and may not in any circumstance be regarded as stating an official position of the European Commission.

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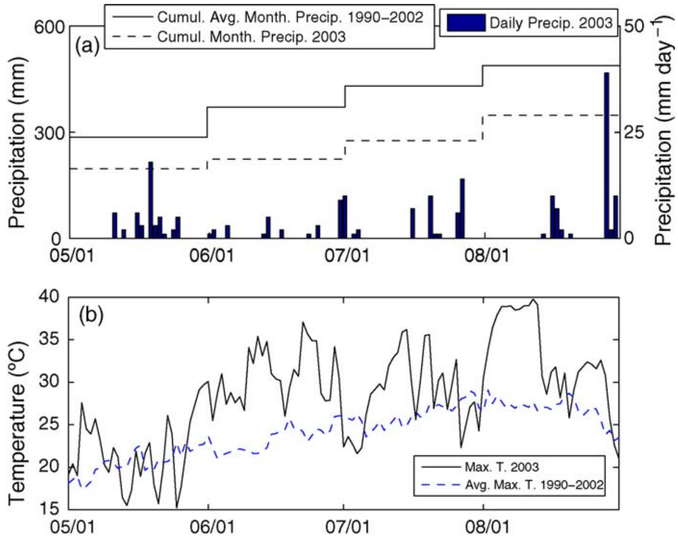

Fig. 1. Progression of precipitation and temperature over late spring and summer 2003 in France at 4.7° longitude and 46.8° latitude from the JRC's MARS 50 by 50 km climate database. Cumulative monthly precipitation averaged from 1990 to 2002 and cumulative monthly precipitation for 2003 (a, left axis) and daily precipitation in 2003 (a, right axis). Maximum daily temperature and maximum daily temperature averaged from 1990 to 2002 (b).

depletion and drought conditions in the summer of 2003. This resulted in reduced latent cooling which amplified the summer temperature extremes. Combined with droughts, cereal crops then risk entering into the grain filling stages under low soil moisture availability. Irrigation provides water to the plant's root zone and allows cooling of the plant's leaves through transpiration. Irrigation effectively alters local climate through the interaction of modified soil moisture conditions, transpiration, air temperature and vapour pressure deficit (Fowler and Helvey, 1974). Plant transpiration and soil water evaporation increase the latent heat flux and thus reduce soil and ambient air temperature. Resulting irrigation cooling is observable over large regions (e.g. California, see Kueppers et al. (2007)). Zaitchik et al. (2006) showed that during the 2003 heatwave the vegetation and surface temperature anomalies were greater for non-irrigated agricultural lands than for forests. This is consistent with the idea that shallow-rooted crops do not have access to deeper reservoirs of water leading to drying and a subsequent increase in sensible heat flux. Similarly, Teuling and Seneviratne (2008) found that cropland density related to the largest spectral albedo changes and total shortwave albedo anomalies.

The 2003 heatwave is used as a case-study to learn about the resilience of rainfed and irrigated maize cultivation to extreme heat and drought. Regional climate models predict that the late 21st century climate in France will increasingly be characterized by summertime drought (Raisanen et al., 2004). If the likelihood of heatwave and drought occurrence indeed increases in a warming climate, this will have important consequences for agricultural water management. The objectives of this paper are the quantification of the actual contribution of (supplemental) irrigation, irrigation interval, and irrigated area to the yield reported at regional level, to yield loss mitigation during the 2003 drought, and to quantify the additional volume of irrigation water used during the drought.

2. Materials and methods

Annual maize yield data were obtained at regional administrative level ('départements') for France from Agreste (2008). Reported yield in a region is a mix between irrigated and rainfed maize. To estimate the yields reported at regional level we performed simulations with a spatialized EPIC model (Williams, 1995; Bouraoui and Aloe, 2007; van der Velde et al., 2009) that runs on a 10 by 10 km grid with relevant meteorological, land use, terrain, soil and management information. Daily meteorological data were obtained from the Joint Research Centre's (JRC) MARS meteorological database given on a 50 by 50 km grid. Land use information was taken from a European land use map developed at JRC (Grizzetti et al., 2007), that combines land cover data of CORINE 2000 (ETC, 2000) with regional crop areas taken from the European farm structure survey (FSS) statistics, thus adding crop specific information to the CORINE agricultural land use classes respecting regional crop areas. Digital terrain information was derived from SRTM (Shuttle Radar Topographic Mission). Soil data were obtained from the European Soil Bureau Database (ESBD 2.0). Sowing dates were determined using the potential heat units program developed at the Texas agricultural experimental station at regional level. The program calculates the total number of heat units required to bring the crop to maturity using long term minimum and maximum temperatures, and optimum and minimum plant growing temperatures and the average number of days for the crop to reach maturity. The minimum temperature was set at 8 °C and the optimal temperature was set at 25 °C. The time to maturity for maize was different in the Atlantic, Alpine, and Continental and Mediterranean regions of France with respectively 180, 185 and 160 days (Bouraoui and Aloe, 2007).

The spatial data were linked to the 10 by 10 km modelling grid. Each 50 by 50 km grid cell of the meteorological database was linked to 25 10 by 10 km grid cells. Crop areas defined in the European land use map (Grizzetti et al., 2007) were tabulated with a class aggregation for each 10 by 10 km grid cell by crop category. Soil data originally at 1 by 1 km were aggregated to the modelling grid (for more details see Williams (1995) and Bouraoui and Aloe (2007)).

This approach allowed us to include relevant soil functions such as water storage capacity in evaluating yield responses and irrigation needs for years characterized by different climatic conditions. Given the high standard of agriculture in France and the generally high fertilizer inputs in French agriculture, we assume that plants do not suffer nutrient stress. Therefore we allowed the model to apply fertilizer automatically according to crop nutrient requirements.

Rainfed and irrigated maize yields are modelled separately and combined using the percentage of maize area that is irrigated (maize irrigation percentage) given by Wriedt et al. (2009a) at a resolution of 10 by 10 km based on EUROSTAT data (Fig. 2). This combined yield is then compared to the reported maize yield at regional level, since it is not specified how irrigated and rainfed maize yields contribute to the reported yield. One simulation was performed without irrigation of maize (rainfed) while other simulations allowed for biweekly, weekly and daily (no water stress) irrigation scheduling to evaluate the impact of different irrigation intervals on crop yields and water use. Irrigation was applied to satisfy plant water stress with a maximum application rate of 60 mm day^{-1} each irrigation interval. This can thus lead to variable irrigation rates from year to year. We consider the model run with a biweekly irrigation interval as our standard irrigation run. Irrigation was legally constrained during the 2003 heatwave and irrigation application therefore may not have been optimal.

Crop parameters were identical in the irrigated and rainfed model runs. Crop growth parameters were kept to the original EPIC crop parameters, except for the harvest index and the energy-biomass conversion that were set to 0.60 [−] and 45 kg ha^{-1} MJ^{-1} m^2 after calibrating to regionally reported yields. The results of these two simulations were combined by weighting

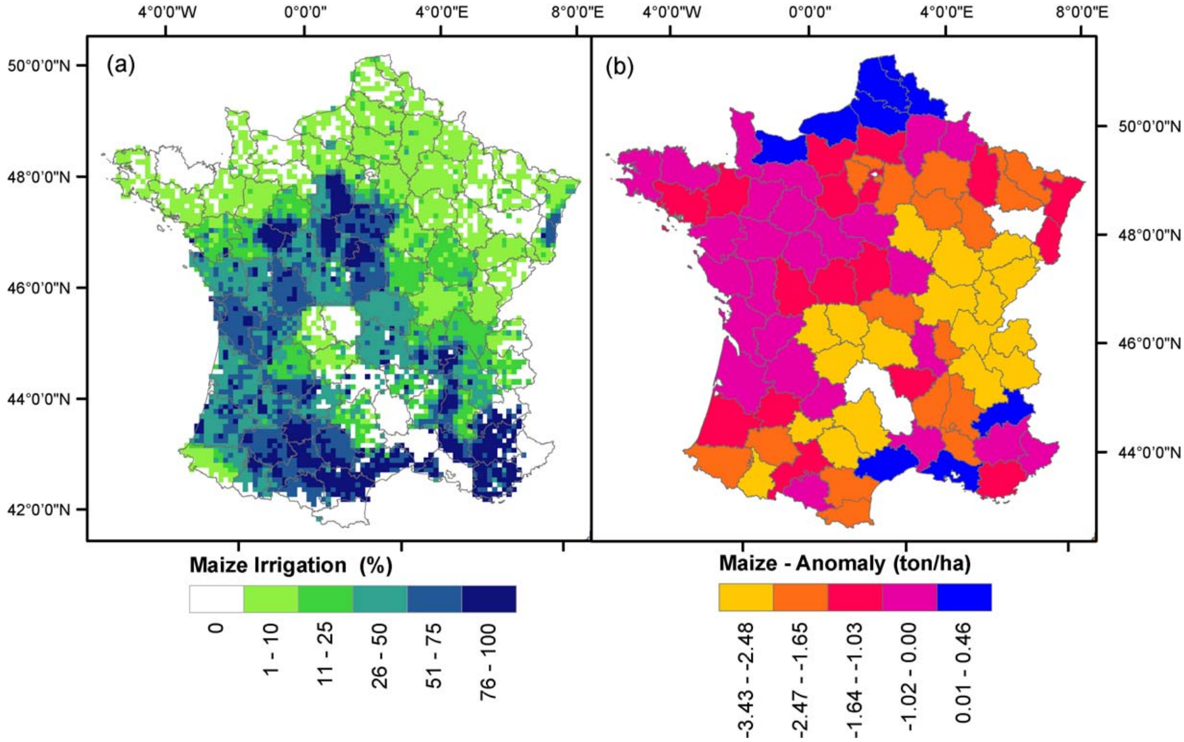

Fig. 2. The percentage of irrigated maize on a 10 by 10 km grid (a) and difference in maize yields (t ha^{-1}) between 2003 and the 2000–2006 average (b).

them by the maize irrigation percentage (Wriedt et al., 2009a) to obtain the final estimated yields and irrigation water use per region. The amount of irrigation water that was used in 2003 was then estimated from the model calculations.

3. Results and discussion

Although most of France was affected by the drought (Trigo et al., 2005), strong regional differences in maize yield anomalies, which we define as the difference between the 2003 maize yield and the 2000–2006 average, can be observed (Fig. 2). Average maize yield in 2003 equalled 7.0 t ha^{-1}, compared to 8.5 t ha^{-1} over the 2000–2006 average (see Table 1). The impact of the 2003 heatwave on maize yield in France is considered for a climatic transition zone between latitudes 44.5° and 48°. In this zone, for the period 1999–2006, significant (positive) relations between yield and irrigation percentage occurred only in 1999, 2003 and 2006 (Table 1). Clearly, a coupling between irrigation and yield only occurs in these regions when a rainfall deficit leads to depleted soil moisture, and the strength of this coupling relates to the severity of the drought.

After calculating the annual regional maize yield differences between 2003 and 2002 yields, it is observed that in 2003, when irrigation is associated with higher yields in the zone between 44.5° and 48°, the percentage maize area irrigated in a region is also related to the capacity to cope with the drought (see Fig. 3). In other words, the difference in yields between 2002, a ‘normal’ to wet year, and the dry year 2003, correlates negatively (R^2 value of 0.46, p-value < 0.001) with the percentage of maize area that is irrigated in a region. This observation illustrates how the percentage of irrigated area and thus the possibility of supplementary irrigation mitigates the negative impact of drought at regional level. This indirectly also validates the maize irrigation percentages calculated earlier.

Model runs of rainfed maize and maize irrigated with a biweekly irrigation interval were combined and weighed by maize irrigation percentage. The resulting modelled yield is compared to reported yield in Fig. 4. The general behaviour in yields from year to year is captured by the model albeit with a wide scatter around the 1:1 line. An underestimation of reported yield can be observed for 2003. The average fertiliser rate for rainfed maize equalled 148 and 229 kg N ha^{-1} for irrigated maize. This is comparable to the expert estimate of 170 kg N ha^{-1} provided by the IFA and FAO for maize in France (IFA, FAO, et al., 2002).

The modelled annual irrigation requirement from 1998 to 2002 (Fig. 5) shows a spatial distribution consistent with the maize area irrigation percentage (Fig. 2). This indicates that the irrigation infrastructure currently in place for maize across France is indeed sufficient under normal climatic conditions. However, during the extreme conditions in 2003, areas normally without the need for irrigation and thus without irrigation equipment, experienced high irrigation requirements.

Regions between 44.5° and 48° latitude were distinguished in classes with low (<5%), medium (5–20%) and high (>20%) maize irrigation percentages (Fig. 6). Reported yield between 1999 and 2002 (Fig. 6a) is described satisfactorily by the model (Fig. 6c) for the different irrigation classes with slight overestimation in regions with low maize irrigation percentage (~0.3 t ha^{-1}) and a slight underestimation for regions with medium ~0.7 t ha^{-1}) and high (~0.3 t ha^{-1}) maize irrigation percentage (Fig. 6e). The maximum yield in the irrigation scenario equalled 18.2 t ha^{-1}. The contribution of irrigation to reported 2003 yield (Fig. 6b) is

Table 1
(i) France’s national maize yield (t ha^{-1}) and (ii) for the study area, France between 44.5° and 48°, R^2 values for linear regression between regional yield maize area irrigation percentage.

Year	99	00	01	02	03	04	05	06
Yield	8.8	8.9	8.5	9.8	7.0	9.0	8.4	8.4
R^2	0.21*	0.02	0.03	0.06	0.56**	0.00	0.02	0.17*

* p-Values < 0.01.
** p-Values < 0.0001.

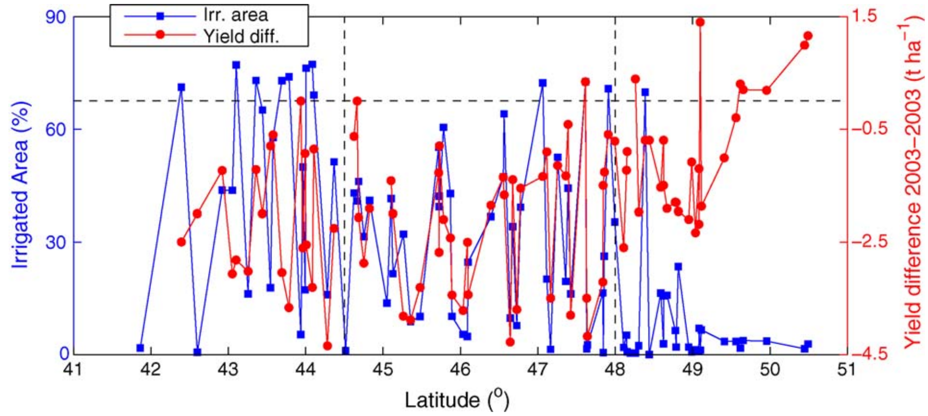

Fig. 3. On a regional basis, percentage of maize irrigated (Wriedt et al., 2009a) and maize yield difference between 2002 and 2003, in relation to latitude. The zone between 44.5° and 48° latitude (cf. Table 1) is indicated.

captured by the model (6d), although modelled yield has a larger range and variation (Fig. 6d). The boxplots in Fig. 6 show that regions in the high irrigation class (>20%) have highest reported (Fig. 6b) and modelled (Fig. 6d) yields in 2003. However, the difference between average modelled and reported data (Fig. 6f) is always negative and increases from low to high irrigation class (progressively equalling ∼0.2, ∼0.8 and ∼1.5 t ha^{-1}).

The differences in averaged 1999–2002 and 2003 yields in regions in the low to medium (<20%) and high maize irrigation classes (>20%) can be compared for both reported and modelled yield to quantify the effect of irrigation area percentage on reported and modelled yield. The difference in averaged 1999–2002 and 2003 reported yield is ∼3.2 t ha^{-1} for regions in the low and medium irrigation class and ∼1.5 t ha^{-1} for the high irrigation class. The difference in averaged 1999–2002 and 2003 modelled yield is ∼3.6 t ha^{-1} for the low and medium irrigation class and ∼2.7 t ha^{-1} for the high irrigation class. In regions in the high irrigation class, modelled irrigation reduced the yield loss by ∼24% $((3.6 - 2.7)/3.6 \times 100)$ while reported data suggest a reduction in yield loss by ∼53% $((3.2 - 1.5)/3.2 \times 100)$ in those regions.

One of the reasons that the effect of irrigation is underestimated during 2003 may be that the predefined biweekly irrigation scheme underestimates the amount of applied water. Irrigation compensates precipitation deficits, and during dry conditions as occurred in 2003, farmers will likely increase irrigation frequency and possibly application volume. In separate irrigation runs that allowed for weekly and daily irrigation, the difference between average modelled and reported data in 2003 reduced to respectively ∼0.6 and ∼0.5 t ha^{-1} in regions in the high irrigation class. The results for regions in the low and medium irrigation class were unaffected. The run with weekly irrigation resulted in a reduction of relative yield loss by ∼42% attributable to irrigation with weekly irrigation scheduling. Daily irrigation scheduling (no water stress) reduced relative yield loss to ∼44%, still short of the ∼53% in the reported data.

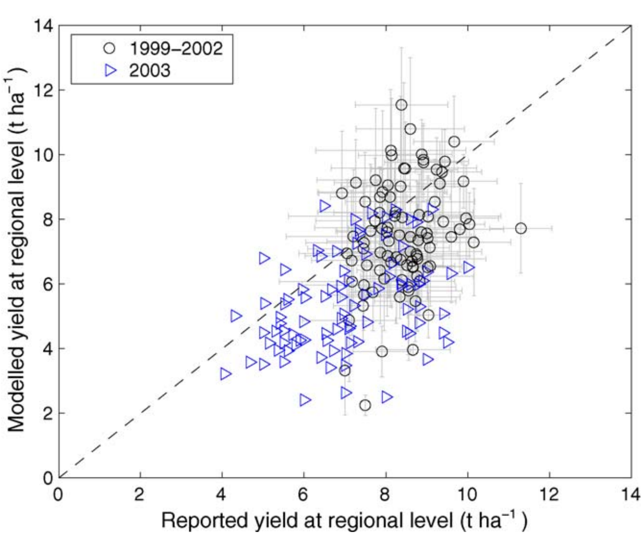

Fig. 4. Reported and modelled maize yield for France's regions averaged from 1999 to 2002 (with error bars indicating one standard deviation) and for 2003. Modelled maize yield is obtained by combining rainfed and irrigated model runs using the previously calculated maize irrigation percentages (Wriedt et al., 2009a). The irrigated run allowed for biweekly irrigation scheduling.

To investigate the change in irrigation from 2002 to 2003 we further quantified the effect of irrigation interval on simulated yield. We expressed the yield obtained with a weekly and biweekly interval as a percentage of the yield obtained under full irrigation (1 day interval, Fig. 7). In 2002 increasing the irrigation frequency from two weeks to one week or 1 day does not have a significant effect on modelled irrigated yield in most regions. Yield loss is greater than 10% in twelve regions with biweekly irrigation scheduling compared to full irrigation in 2002. In 2003, on the contrary, biweekly irrigation leads to ∼20% lower yields in ∼30% of the regions. Increasing the irrigation frequency in the model from two weeks to one week or even 1 day will thus not have large consequences on modelled irrigated yield during normal meteorological conditions in most regions. Irrigation volume does increase considerably during 2003 as a function of irrigation frequency compared to 2002 (Table 2). The difference in median 2002 and 2003 irrigation rates with biweekly, weekly and daily scheduling increased with respectively 69, 160 and 187 mm year^{-1}.

A possible explanation for the discrepancy between modelled and reported yield in areas with different irrigated maize area percentages may be that the irrigation percentages are fixed and we thus do not allow for dynamic expansion or shrinkage of irrigated areas in response to climatic conditions. Another reason for the discrepancy may be that the model lacks a coupling between atmosphere and soil. Through its cooling effect on the ambient air temperature, irrigation will also indirectly reduce heat stress and thus delay harvesting and allow for a longer grain filling period compared to rainfed maize. Saadia et al. (1996), for example, found that mean maize-ear temperature was ∼3 °C lower and mid-height canopy air was 2 °C lower in sprinkler irrigated maize compared to rainfed maize in experiments carried out in the summer of 1994 in the South of France. EPIC has been used in modelling controlled irrigated maize field experiments with good

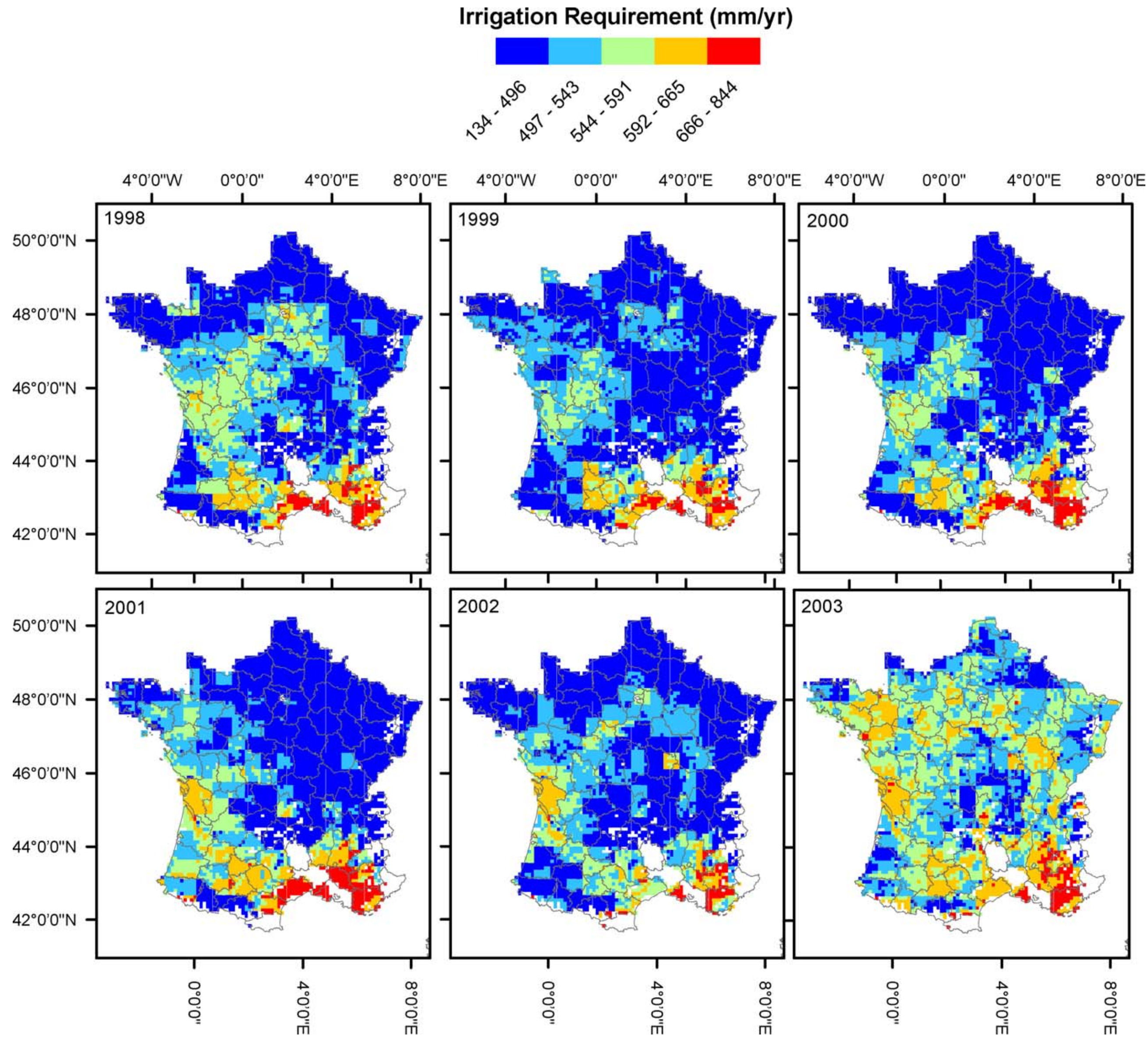

Fig. 5. Modelled irrigation requirement (mm year^{-1}) from 1998 to 2003.

accuracy (for example see Cabelguenne et al., 1999). Our large-scale EPIC application also does not adequately capture specific local conditions, distinguish sufficiently between maize crop varieties, and does not allow for adaptive interventions by the farmer, and therefore comparison between reported and modelled yields at administrative level remains difficult. Other effects which are not included in the model and which influence regional maize yield include weeds, pest and diseases that may be influenced by agricultural management, as well as socio-economic factors, farm size, farm intensity and regional farm diversity (Reidsma et al., 2009).

Notwithstanding the previous remarks, the capability to represent the inter-annual changes gives confidence that the model can be used for a relative assessment. The differences in yields between 2002 and 2003 for reported and modelled yields correlate (R^2 value of 0.25, p-value < 0.0001). This suggests that the model represents crop management and irrigation practices and their influence on yield fairly correct in a relative sense. The differences in yields for reported as well as modelled yield correlate with the annually averaged maximum daily temperature with R^2 values of respectively 0.30 (p-value < 0.0001) and 0.40 (p-value < 0.0001). This indicates that maximum temperature is a crucial parameter determining both reported and modelled yield.

An increasing percentage of the yield can be attributed to irrigation in regions with irrigation shares up to 40%, when comparing 2003 with 2002 using biweekly irrigation scheduling (Fig. 8a). Nevertheless, these regions still show the largest negative yield difference with 2002. Our modelling results suggest that the yields would probably have been affected even worse without supplemental irrigation. Differences in yield were less negative in regions with irrigation percentages >40%. Obviously, the capacity to compensate does not make a clear additional difference in regions already considerably dependent on irrigation (Fig. 8b). Therefore, the difference in irrigation rates between 2002 and 2003 tend to decrease with increasing irrigation percentage (Fig. 8c). The difference in atmospheric evaporative water demand between 2002 and 2003 required irrigation rates to increase by 70–100 mm year^{-1} comparing biweekly irrigation intervals for 2002 and 2003. Since increasing the irrigation frequency from two weeks to one week had a significant impact on maize yield in 2003, but not in 2002, the most appropriate difference in irrigation rate is provided by the difference between the biweekly rate in 2002

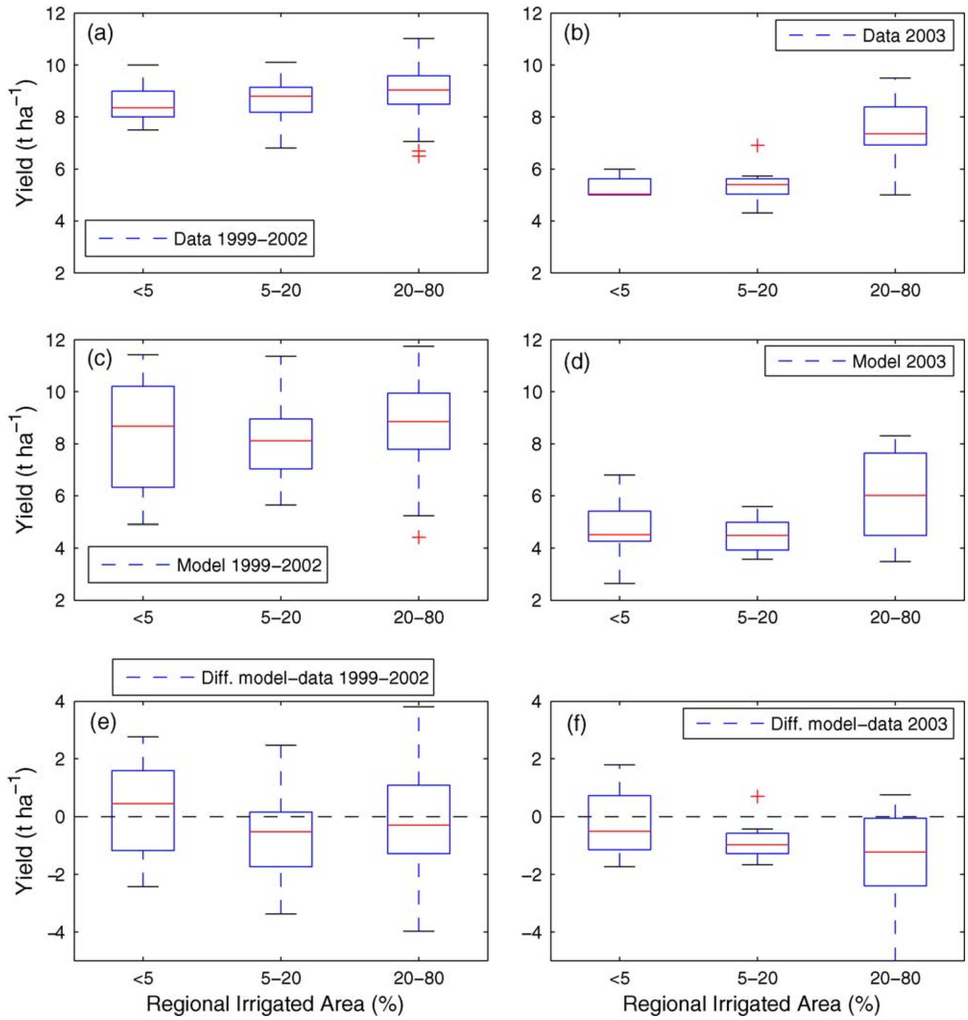

Fig. 6. The impact of the percentage of maize area that is irrigated on reported (a and b) and modelled (c and d) regional maize yield for the study area between 44.5° and 48° latitude. Reported and modelled yields and their difference (e and f) are shown for 1999–2002 and 2003 in relation to low, medium and high irrigation class. The irrigated run allowed for biweekly irrigation scheduling. The number of observations from low to high irrigation class: $n = 5$ (for the model $n = 6$), 10 and 27).

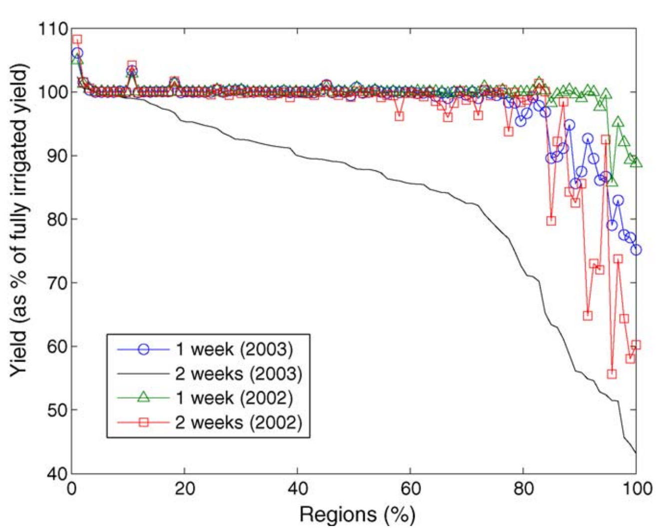

Fig. 7. The yield loss associated with weekly and biweekly irrigation intervals expressed as a percentage of fully irrigated maize yield for 2002 and 2003. Results are ordered by increasing 2003 yield loss by region associated with a biweekly irrigation interval.

(484 mm year^{-1}) and the weekly rate in 2003 (743 mm year^{-1}) which equals 259 mm year^{-1}. Taking the difference in weekly scheduling of 157 mm year^{-1} as a conservative lower bound, this estimate corresponds to an increase in irrigation water use of between ~1068 million m^3 and ~1761 million m^3, assuming ~0.68 million hectares of irrigated maize.

Although irrigation may be beneficial in mitigating the impacts of drought on yield, increased water abstractions may have negative impacts that may include increased groundwater depletion, increased soil salinity, increased abstraction costs and lower water availability for other uses. Expansion of irrigation infrastructure in response to drier conditions may exacerbate these problems. Careful policy will have to be developed to mitigate on one hand the impact of heatwaves and droughts on

Table 2
Modelled irrigation rates (mm year^{-1}) in 2003 and 2003 with biweekly, weekly and daily irrigation scheduling.

	2002			2003		
	Median	Min	Max	Median	Min	Max
Two weeks	484	292	827	553	454	777
One week	583	364	1160	743	546	1106
Day	762	523	1652	949	713	1671

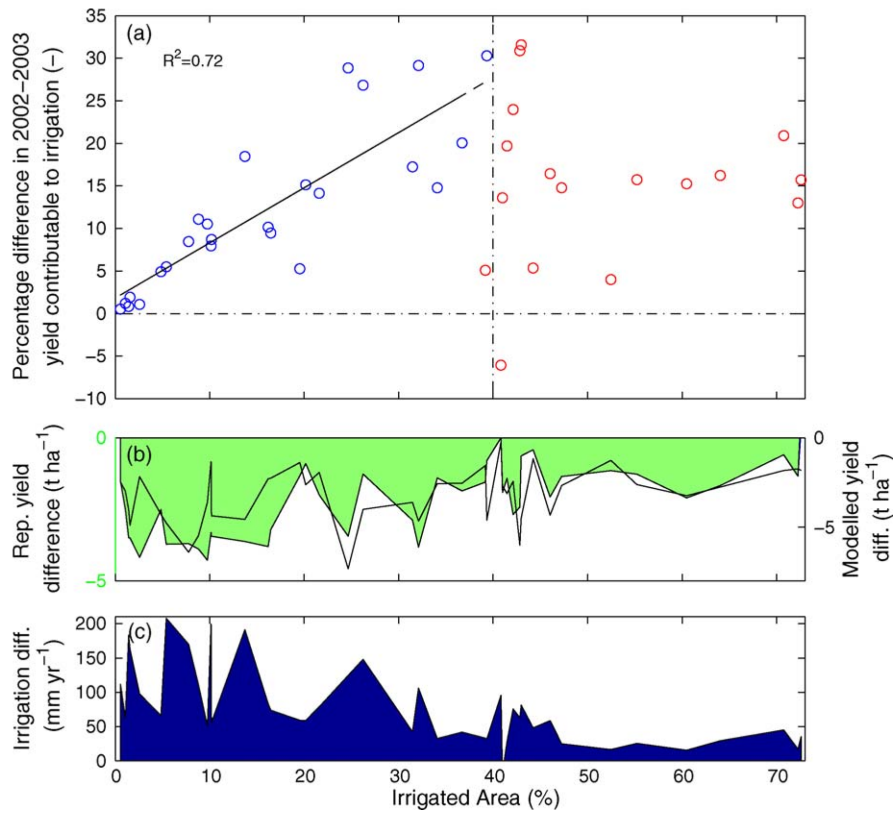

Fig. 8. Percentage of irrigated maize by region and the percentage difference between 2002 and 2003 of the yield that can be attributed to irrigation (a), irrigation percentage vs. absolute difference in yield of both reported and modelled data (b, respectively area on left *Y*-axis and line on right *Y*-axis) and irrigation percentage vs. difference in irrigation rate (c).

agricultural production, while on the other hand ensuring a minimal impact on water resources. The economic benefit that is derived from supplemental irrigation in hot summers, or when droughts occur, should be carefully weighed against environmental impacts. A short duration heatwave can have long term effects for water resources management including the depletion of groundwater storage and irrigation reservoirs. Policy options include a promotion of crops that are less water intensive in southern regions and increased support effort for those irrigation practices that have proven to be most efficient. Unregulated groundwater abstraction is an example of the ‘tragedy of the commons’ and assessments like these might aid in an increased common ‘groundwater wealth’ through improving informed management.

4. Conclusion

During the 2003 heat wave in France, the contribution of irrigation to minimizing yield loss depended on the percentage of the maize area that was irrigated. In areas with less than 40% irrigated area the compensation effect is related to irrigation percentage, while in areas with more than 40% irrigated area an increase in the percentage of irrigated area was no longer related to increased mitigation. Although the current irrigation infrastructure is sufficient under normal conditions, in 2003 the need for irrigation also increased considerably in those areas without irrigation infrastructure.

In our modelling studies, increasing the irrigation frequency in the model from two weeks to one week had a significant impact on maize yield in 2003, but not in 2002. The average irrigation rate with weekly irrigation scheduling equalled 743 mm year^{-1} in 2003. Compared to weekly and biweekly irrigation scheduling in 2002, there is an increase of respectively 157 mm year^{-1} and 259 mm year^{-1}. The estimated increase in irrigation water use of between ~1068 and ~1761 million m^3 from 2002 to 2003 highlights the need for careful management of water resources to anticipate the impacts of heatwaves and droughts which are expected to increase in frequency in the future.

Increasingly policymakers will have to give incentives to restructure, redesign and make irrigation infrastructures more efficient and decide where and where not, irrigation has the highest marginal benefit with respect to water resources. This requires choices that will decide agriculture’s future water use efficiency that should be based on calculating where the comparative advantage of (supplemental) irrigation is highest.

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