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ORIGINAL ARTICLE

Impact and adaptation opportunities for European agriculture in response to climatic change and variability

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Abstract Climate change, involving changes in mean climate and climatic variability, is expected to severely affect agriculture and there is a need to assess its impact in order to define the appropriate adaptation strategies to cope with. In this paper, we projected a scenario of European agriculture in a +2°C (above pre-industrial levels) world in order to assess the potential effect of climatic change and variability and to test the effectiveness of different adaptation options. For this purpose, the outputs of HadCM3 General Circulation Model (GCM) were empirically downscaled for current climate (1975–2005) and a future period (2030–2060), to feed a process-based crop simulation model, in order to quantify the impact of a changing climate on agriculture emphasising the impact due to changes in the frequency of extreme events (heat waves and drought). The same climatic dataset was used to compare the effectiveness of different adaptations to a warmer climate strategies including advanced or delayed sowing time, shorter or longer cycle cultivar and irrigation. The results indicated that both changes in mean climate and climate variability affected crop

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growth resulting in different crop fitting capacity to cope with climate change. This capacity mainly depended on the crop type and the geographical area across Europe. A +2°C scenario had a higher impact on crops cultivated over the Mediterranean basin than on those cultivated in central and northern Europe as a consequence of drier and hotter conditions. In contrast, crops cultivated in Northern Europe generally exhibited higher than current yields, as a consequence of wetter conditions, and temperatures closer to the optimum growing conditions. Simple, no-cost adaptation options such as advancement of sowing dates or the use of longer cycle varieties may be implemented to tackle the expected yield loss in southern Europe as well as to exploit possible advantages in northern regions.

Keywords Extreme events · Drought · Heat wave · Global warming · Agriculture · Adaptation

1 Introduction

The results of recent global climate monitoring as well as climate projections stress that future climate will be significantly different than that experienced in the past (Rosenzweig et al. 2007). These changes are expected to affect many economic sectors, including agriculture, forestry, energy consumption, and tourism (Hanson et al. 2007) and a global mean temperature change of 2°C (above pre-industrial levels) is considered to be the critical threshold beyond which climate change impacts may become unacceptably dangerous (IPCC 2007). Building on these premises, EU policy aims to curb global warming below 2°C for the turn of this century (EC 2007) requiring significant mitigation and adaptation solutions to ensure a tolerable transition ("soft landing") to a warmer climate. It follows that impact assessment of the +2°C scenario is a critical tool to develop future response strategies in different sectors and systems.

Since agricultural practices are climate-dependent and yields vary from year to year depending on the weather, the agricultural sector is particularly exposed to climatic change. Understanding the potential impacts on agriculture of a warming climate has thus become increasingly important and is of primary concern particularly to ensure the sustainability of agricultural systems as well as for policy-making purposes (Howden et al. 2007).

Adaptation is undoubtedly an important component of any policy response to climate change in this sector (Mizina et al. 1999; Reilly and Schimmelpfennig 1999). Studies show that without adaptation, climate change may create considerable problems related to agricultural production and agricultural economies and communities in many areas; but with adaptation, vulnerability can be reduced and there are numerous opportunities to be realized (Nordhaus 1991; Rosenzweig and Parry 1994; Smit et al. 1996; Wheaton and McIver 1999; Smit and Skinner 2002; Wall and Smit 2005). A number of adaptation strategies have been proposed and tested in simulation studies (Adger et al. 2007) in order to evaluate their efficacy in reducing the negative impact or exploit possible beneficial effects of a changing climate. These strategies included changes in crop species, cultivar and sowing dates (Alexandrov et al. 2002; Tubiello et al. 2002; Adams et al. 2003; Butt et al. 2005; Giannakopoulos et al. 2009). These adaptations singly or in combination have the potential to reduce negative climate change impacts and to take advantage of positive ones (Howden et al. 2007).

Effective adaptation strategies, however, should be adopted bearing in mind that climate change includes not only long-term changes in mean conditions, but also a change in the frequency and magnitude of extreme weather events (Hulme et al. 1999; Porter and Gawith 1999; Schneider et al. 2007; Moriondo et al. 2010). Crop yield is largely determined by average climate conditions, but is also affected by irregular or extreme conditions deviating from the mean growing season conditions, in particular—droughts and heat waves (Mearns et al. 1984; Reilly 1995; Risbey et al. 1999; Challinor et al. 2005). The summer heat wave of 2003 (Schär et al. 2004), taken as an indicator of the future climate change, accompanied by precipitation deficits, resulted in reduced cereal production in Europe by 23 MT with respect to 2002. This was the result of higher temperatures that led to an increasing in the developmental rate and resulted in a shorter time for biomass accumulation, combined with a greater frequency of extreme events, in terms of maximum temperatures and longer dry spells, which directly affected crop fertility and seed set (Olesen and Bindi 2004). Major concerns result, therefore, from model-based climate projections for the 21st century, which show increases in both the duration and magnitude of both heat stress and dry spells as well as in the precipitation intensity in many European regions (Beniston et al. 2007).

On these premises, this study aims first to assess the impact of climatic change on EU agriculture of a +2°C change, considering changes in both mean climate ad climate variability. This assessment was then considered as a basis to test the effectiveness of specific adaptation strategies to alleviate the expected adverse impacts or to exploit possible positive effects of climatic change. Specifically, the results of a GCM were coupled with the process-based Cropsyst model (Stockle et al. 2003) to simulate responses of sunflower (*Helianthus annuus* L.), soybean (*Glycine max* L.), spring and winter wheat (*Triticum aestivum* L. and *Triticum turgidum* L.subsp. *durum*, respectively) to climate change and variability. The effectiveness of different adaptation options, including advanced or delayed sowing time, shorter or longer cycle cultivars and irrigation, in alleviating the expected adverse impacts or in exploiting possible positive advantages of climatic change were tested.

Due to the coarse GCM resolution, an empirical downscaling procedure was first set up in order to reproduce, on a scale suitable for impact assessment on a regional scale, the future climate at a global warming of 2°C. This procedure, based on the use of a weather generator (LARS WG, Semenov and Barrow 1997), allowed consideration of both change in mean climate as well as changes in the climate variability for future climate simulations, as required for this assessment. The results are discussed in terms of which mechanisms underly the processes of adaptation to climate change in agriculture.

2 Material and methods

2.1 Climate data

A downscaling procedure was set up in order to reproduce, on a scale suitable for impact assessment in agriculture (i.e. 50 km×50 km), the future climate at an average global warming of 2°C. This procedure was based on the use of the LARS WG weather generator that allowed including changes in mean climate as well as in climate variability as derived from a GCM in future climate simulations. The results of HadCM3 (Pope et al. 2000), centred on 1975–2005 were statistically downscaled, to reproduce, on a regional scale, the baseline period. According to the result of New (2005) and Giannakopoulos et al. (2009), the time-slice 2030–2060, as simulated by the HADCM3 A2 scenario, was selected to represent the period corresponding to a global average increase of +2°C with respect to the pre-industrial period.

Following the LARS WG procedure for downscaling, available observed daily weather data for a given site were used to determine a set of parameters for probability distributions of weather variables as well as correlations between them (calibration stage). This set of parameters was then used to generate the synthetic weather time series describing the reference period 1975–2005 and as a baseline to be perturbed using forcing factors derived from the GCM.

In this work observed daily data (daily minimum and maximum temperature, rainfall and global radiation, [Tmin, Tmax, R and Rad, respectively]) for the period 1975–2005, spaced 50×50 km over the EU domain (MARS project, http://mars.jrc.ec.europa.eu) were used for the local calibration of the stochastic weather generator. After calibration, 100 years of synthetic daily weather data were produced for each one of 2,248 grid points to represent the baseline period over the domain (Fig. 1).

The results of HadCM3 in A2 scenario for the time-slice 2030–2060 were used to derive the forcing factors for the downscaling procedure. These were computed for each one of 304 GCM grid points covering the domain (Fig. 1), as monthly average differences of Tmin, Tmax, R and Rad between the future and the relevant baseline period (1975–2005). For temperature and rainfall the relative change in standard deviation and in duration of wet and dry spell were also calculated. Finally, forcing factors calculated for each GCM grid were applied in the downscaling procedure to perturb the relevant climatology of the observed dataset generating stochastically 100 years of daily data for each 50×50 km grid point.

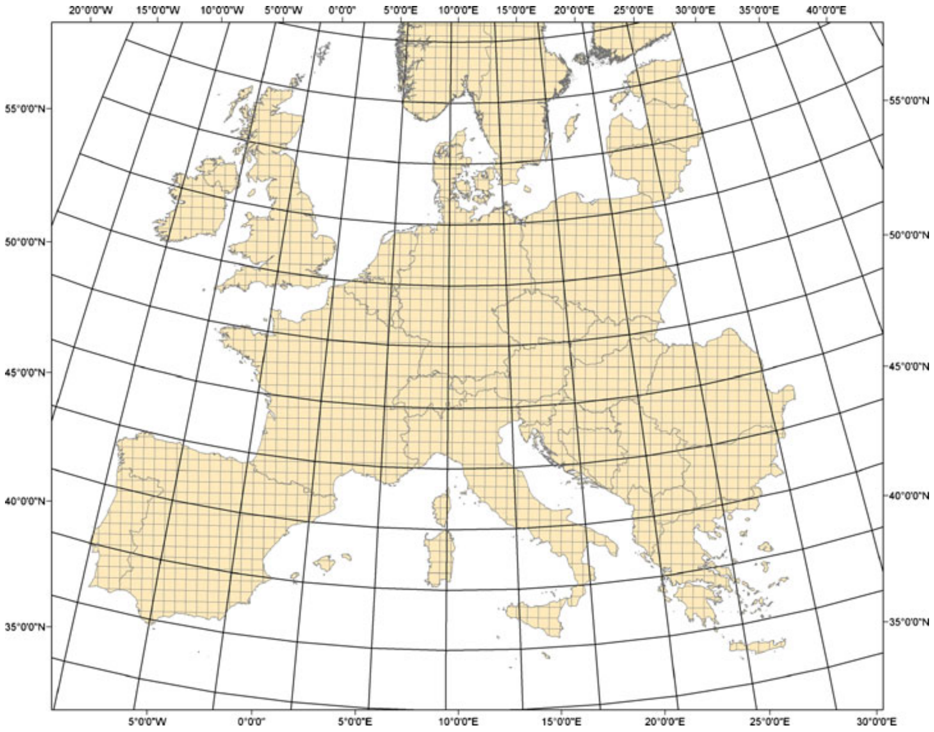

Fig. 1 Study region. HadCM3 GCM grid (*bold line*, 3.75° Lon×2.5° Lat) overlaid to the grid of the observed dataset (*thin line*, 0.5°×0.5°). HadCM3 climate perturbing factors (i.e. the monthly average differences of Tmin, Tmax, R and Rad between the future [2030–2060] and the baseline period [1975–2005]) were statistically downscaled over the relevant grid points of the observed dataset

The effectiveness of LARS WG in reproducing present climate was preliminary tested carrying out a statistical comparison of the weather generator outputs with the observed data over a sample of 100 grid points randomly selected across the domain.

Generated and observed mean monthly temperatures and rainfall were compared to provide a general overview of LARS WG performances on the mean local climate generation. Additionally, the quarterly probability distributions for length of wet and dry series, frost (days with minimum temperature less than 0), and hot series (days with maximum temperature greater than 30) and the monthly probability distributions for precipitation were compared to test LARS WG reliability in simulating climate variability. The probability distributions for the generated and observed data were compared using the chi-square goodness of fit test. The means were compared using the *t*-test. In each case a *p*-value was calculated, which is used to accept or reject the hypotheses that the two sets of data belong to the same distribution.

After validation, the results of the statistical downscaling procedure were used as input variables to drive CropSyst growth model simulations for the baseline and future periods on a European scale.

2.2 CropSyst model

CropSyst is a multi-year, multi-crop, daily time-step crop-growth simulation-model. It simulates soil-water budget, soil-plant nitrogen budget, crop canopy and root growth, phenology, dry matter production, yield, residual production and decomposition, and erosion. The user can input management parameters such as sowing date, cultivar genetic coefficients (photoperiodic sensitivity, duration of grain filling, maximum Leaf Area Index, etc.), soil profile properties (soil texture, thickness), fertilizer and irrigation management, tillage, atmospheric CO_2 concentration etc.

The simulation of crop development in CropSyst is mainly temperature-dependent and it is based on the thermal time required to reach specific development stages. Thermal time is calculated as growing degree-day (GDD, °C day^{-1}) defined as the sum of differences between the average of the daily maximum and minimum temperatures and a base temperature, usually 10°C, accumulated throughout the growing season (starting from sowing until harvest). In the simulation of crop development other environmental aspects, such as day-length, low temperature requirements, i.e. vernalization and soil water content, are also taken into consideration. In particular for winter crops the vernalization process provides the exposure to low, non-freezing temperatures to enter the reproductive stage and GDD accumulation is limited until vernalization requirements are met. In the post-vernalization phase, longer days lead to a linear increase in the development rate in the range between 8–15 h. The phenology of summer crops such as maize, soybean and sunflower is only temperature dependent with no vernalization requirements.

The core of the model is the determination of the biomass potential growth under optimal conditions (without water-nitrogen stress) based both on crop potential transpiration and crop intercepted photosynthetic active radiation. The potential growth is then corrected by water and nitrogen limitations, if any, and the actual daily biomass gain is thus determined. The simulated yield is obtained as product of the actual total biomass cumulated at physiological maturity and the harvest index (HI = harvestable yield/above-ground biomass).

Furthermore, the use of a modified version of the model allowed consideration of the effect of increasing atmospheric CO_2 concentration on potential evapotranspiration, crop water use efficiency (WUE, [Kg m^{-3}]) and radiation use efficiency (RUE, g MJ^{-1}) (Tubiello et al. 2000).

2.3 Heat and drought stress impact

In CropSyst, drought stresses occurring at anthesis and grain filling period are already considered as yield-reducing factors. A mean water stress index (WSF, ranging from 1 [no stress] to 0 [maximum stress]) is calculated during these reproductive stages and used to proportionally decrease the HI according to equation:

$$WSF = (1 - AvStress_a) \times \left(1 - AvStrss_{gf}\right) \tag{1}$$

Where WSF is the water stress factor ranging from 1 (any water stresses neither during anthesis [$\text{AvStress}_{\text{a}}$] or grain filling [$\text{AvStress}_{\text{gf}}$]) to 0 (at least a maximum water stress during anthesis or grain filling).

By contrast, CropSyst, like other widely used models, does not include the simulation of heat stress on final yield. This results in a potential underestimation of climate change impact in agriculture (Porter and Gawith 1999) since heat stresses at anthesis have been widely demonstrated to be a yield reducing factor (Challinor et al. 2005).

In this work, heat stress impact on final yield was introduced into CropSyst model after the approach proposed by Moriondo et al. (2010). This model relies on the simulation of final HI as function of the grain filling duration (GF, expressed as the number of days from fruit-set to maturation) and the daily increase of HI (dHI/dt, provided that it is constant during the whole GF [Moriondo et al. 2005]). Accordingly:

$$HI = \frac{dHI}{dt} \times GF \tag{2}$$

The approach proposed by Challinor et al. (2005) and adapted to CropSyst by Moriondo et al. (2010), was then used to calculate the impact of heat stress events on dHI/dt during anthesis for winter and summer crops. Such episodes were identified by comparing the Tmax to a critical value Tcr, above which grain-set starts to be reduced up to the minimum level corresponding to a severe heat shock (Tlim, the temperature at 0% grain-set).

For both type of crops high temperature episodes during pre- and post-anthesis were demonstrated to decrease grain-set (Porter and Gawith 1999; Chimenti and Hall 2001). Accordingly, a period included between −5 to +8 days from full anthesis date was assumed as sensitive to the effect of heat stress (Tashiro and Wardlaw 1990). with Tcr=31°C and Tlim=40°C at full anthesis (Narciso et al. 1992).

For each high temperature episode (Tlim>Tmax>Tcr) the impact on the grain set was calculated as:

$$P = 1 - \frac{T\max - Tcr}{T\lim - Tcr} \tag{3}$$

The overall heat stress impact on dHI/dt was then calculated over the period by:

$$\frac{dHIa}{dt} = \frac{dHIu}{dt} \times \left[1 - \frac{(Pcr - Ptot)}{Pcr}\right] \quad \text{for Ptot} < \text{Pcr} \tag{4}$$

where Ptot (ranging from 0 to 1) is the lowest P calculated over the period, Pcr is the critical fractional grain-set below which dHI/dt begins to be reduced from its non-stressed value (dHIu/dt) to the actual value (dHIa/dt). For both crop type, the same critical fractional grain-set (Pcr=0.85) was assumed. For a more detailed explanation of the approach, please refer to Challinor et al. (2005).

Final HI was then calculated as the product of dHIa/dt and GF as decreased by the effect of drought stress WSF. Yield was then recalculated as the product of the resulting HI and the total above ground biomass (AGB) as simulated by CropSyst.

$$Yield = AGB \times \frac{dHIa}{dt} \times WSF \times GF \tag{5}$$

2.4 Crop model set-up

The results of statistical downscaling, i.e. 100 years of daily Tmin, Tmax, R and Rad, representing the baseline period (1975–2005) and future climate scenarios A2 (2030–2060), were processed and adapted to the needs of the weather files managed by CropSyst model. Both winter and summer crops were considered in this work. Durum wheat (including vernalization process) was selected for winter crops whereas soft wheat (not including vernalization process), soybean and sunflower represented the summer crops.

Durum wheat simulations for the baseline and the future period were limited to the Mediterranean basin which at the present time represents its main cultivated area.

To ensure a likely simulation of the water balance at grid point scale, the specific soil properties (thickness and texture) relevant to each grid point were extracted from the European soil database *Eusoils* (ESDBv2 Raster Archive—published by the European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, http://eusoils.jrc.it/; resolution 10 Km × 10 Km). The soil class having the higher frequency within each 50 × 50 km grid point grid was considered as representative of the whole grid point.

In the present scenario as well as in the future business-as-usual scenario (BAU, +2°C not including adaptation) optimal nitrogen fertilization (150 kg ha^{-1} split 50% at sowing and 50% at anthesis stage) and no irrigation were assumed. Tillage (primary disc plough at 20 cm depth) was set in late summer before sowing for winter crops and 10 days before sowing date for summer crops (sunflower and soybean).

Sowing time was simulated both in present and for the BAU scenario starting from a fixed date until thermal requirements specific for each crop were satisfied. In particular sowing time for winter crop was simulated starting from 20th November whereas for spring-summer crops the initial date was set from 1st March.

Using this configuration, the CropSyst model was firstly tested and calibrated to faithfully reproduce on a regional scale yield of the considered crops for the baseline period.

After the calibration process, winter and summer crop yield were simulated for 1975–2005 and 2030–2060 time slices. For the latter both BAU and adapting scenarios were considered.

Adaptation options for the 2030–2060 period included:

- shifting in sowing date (±15 days with respect to BAU sowing time),
- use of cultivar with a longer/shorter growth cycle (±20% for each phase duration with respect to those used in BAU)
- application of irrigation to rain-fed crops (available water content was set not to be reduced below 40% of the field capacity)

Atmospheric CO_2 concentration was set to 350 ppm for the baseline and 550 for the period 2030–2060. For doubling of atmospheric CO_2 from 350 to 700 ppm, crop RUE was set to increase by 30% for both summer and winter crops.

For each simulation run, including the baseline period (1975–2005) and the future period (2030–2060) in a BAU scenario as well as the relevant adaptation options, the dates of main phenological stages (emergence, anthesis and physiological maturity), the number of heat and drought stress events during the reproductive stage which decreased potential yield, the potential and actual evapotranspiration (PET and AET, respectively), AGB and yield were recorded.

3 Results

3.1 Downscaling validation

The results indicated a general overall agreement between observed and simulated data both in terms of mean values and climate variability.

Minimum and maximum mean monthly temperatures were well reproduced by LARS WG, especially in autumn-winter (errors within 6% of test cases) whereas the errors slightly increased in spring and summer (up to 13% of test cases) (Fig. 2). The quarterly probability distribution of frost spell was also well represented by LARS WG for the test cases, presenting highest errors ranging from 15% in winter to 12% in autumn. The simulations of hot spells showed an overall error of 13% in summer (Fig. 3).

The mean monthly rainfall presented limited errors (up to 8% of the test cases) and also monthly probability distributions were well simulated with errors included between 2% and 11% (Fig. 2). Dry and wet spell were well simulated in all the seasons but in summer the overall error reached 14% and 16% of test cases, respectively (Fig. 3).

3.2 Crop model calibration

The calibration was performed using the output of LARS WG procedure as obtained for the baseline period (i.e. no forcing factors) as input of Cropsyst. The preliminary dataset, consisting of 2,600 grid points spaced 50 by 50 Km, covering the EU27, was first filtered removing those grid points not belonging to the to the class “arable lands” as defined in CORINE 2000 land cover database.

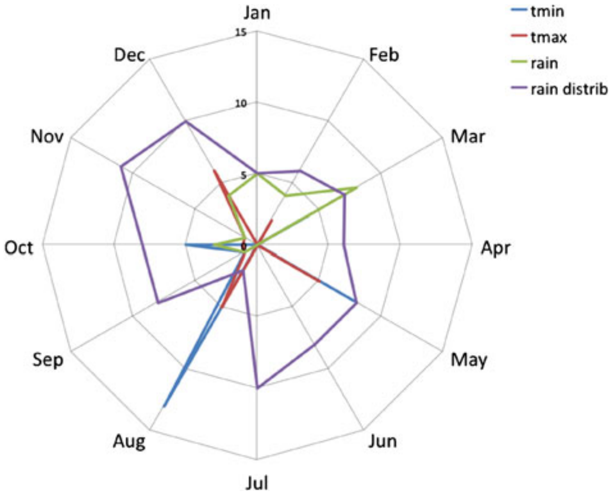

Fig. 2 Error in reproducing the observed monthly average minimum (*blue line*) and maximum temperature (*red line*), rainfall (*green line*) and rainfall distribution (*purple line*) using LARS WG. Data are expressed as percentage calculated over 100 test cases randomly selected across the domain

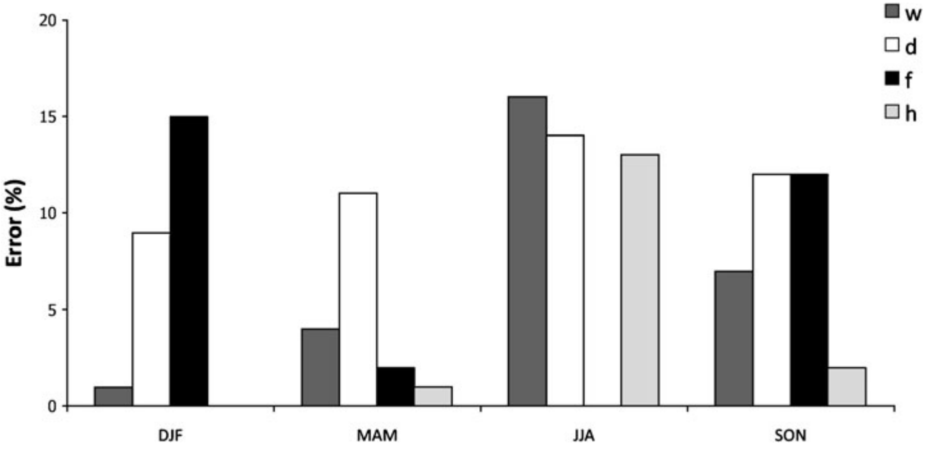

Fig. 3 Error in reproducing the seasonal probability distributions (DJF=winter; MAM=spring; JJA=summer; SON=autumn) for length of wet series (w), length of dry series (d) (dark grey and white histograms, respectively) and the length of frost series (f) (days with Tmin less than 0, black histograms) and hot series (h) (days with Tmax greater than 30, light grey histograms). Data are expressed as percentage calculated over 100 test cases randomly selected across the domain

In the first iteration of the calibration process, the average crop yield calculated for each grid point on a random sample of 30 years were aggregated at NUT1 level and compared to the relevant average observed yield as extracted by EUROSTAT database (http://epp.eurostat.ec.europa.eu) for the period 1995–2007. Correlation coefficient (*r*) and the root mean square error (RMSE) were used as goodness-of-fit indicators. Second, both WUE and RUE default values were iteratively tuned, within the range of values reported in literature for each crop, in order to maximize the goodness-of-fit indicators relevant to each crop.

While for soybean and sunflower the WUE and RUE default specific parameters in Cropsyst provided the best results in terms of both *r* (0.7 and 0.85 for soybean and sunflower respectively, highly significant for $P<0.01$) and RMSE (0.59 and 1.25 Mg ha^{-1}), for spring and durum wheat only *r* resulted highly significant ($P<0.01$; 0.78 and 0.77 respectively for durum and soft wheat respectively) whereas crop yield was highly underestimated causing a RMSE of 1.3 Mg and 1.7 Mg ha^{-1} respectively. The final result of calibration, corresponding to a WUE=5.5 Kg m^{-3} and RUE=3.5 g MJ^{-1} for durum wheat and to WUE=6.8 Kg m^{-3} and RUE=4.2 g MJ^{-1} for spring wheat, resulted into an improved match between observed and simulated data for both durum and soft wheat with an *r* ranging from 0.8 (durum) to 0.82 (soft) with a relevant RMSE of 0.9 and 1.1 Mg ha^{-1}.

3.3 Climate change impact in BAU scenario

3.3.1 Climate trend in a +2°C scenario

The general picture, depicted by HadCM3 for 2030–2060 time slice over the European domain, indicated a general increase of temperature (1.5°C) and a slight rainfall decrease (3.5%) with respect to the baseline period 1975–2005.

Temperature asymmetrically increased along the year, with different seasonal effects and trends for the northern and southern Europe. In the northern regions (roughly above the latitude of 50° N), higher increases were observed in winter whereas in southern Europe the higher temperature increases were recorded in summer. The variability of temperature generally increased proportionally as the temperature increased, resulting in a higher frequency of “hot” extreme events for crops (i.e. Tmax >31°C) in 2030–2060 (Fig. 4).

A clear spatial and temporal pattern in the change of rainfall distribution emerged (Fig. 5). Annual rainfall generally is projected to increase in Northern Europe above the latitude of about 55° N, where the largest increases, included between 0 and 15%, are expected for winter and spring. By contrast, a sensible rainfall decrease can be detected for the regions below 55° N, especially over the Mediterranean basin. Over these areas, the summer period is projected to exhibit a rainfall decrease up to 35% with respect to the baseline period. As a consequence of this trend, wet spell duration generally tends to increase in the regions above 55° N while below this limit, it tends to decrease. The Mediterranean area, in summer, is mostly affected by this trend.

3.3.2 Impacts on crops in a +2°C scenario

Both change in mean climate and climate variability affected crop growth resulting in different crop fitting capacity to cope with climate change. This capacity mainly depended on the crop type and the geographical area.

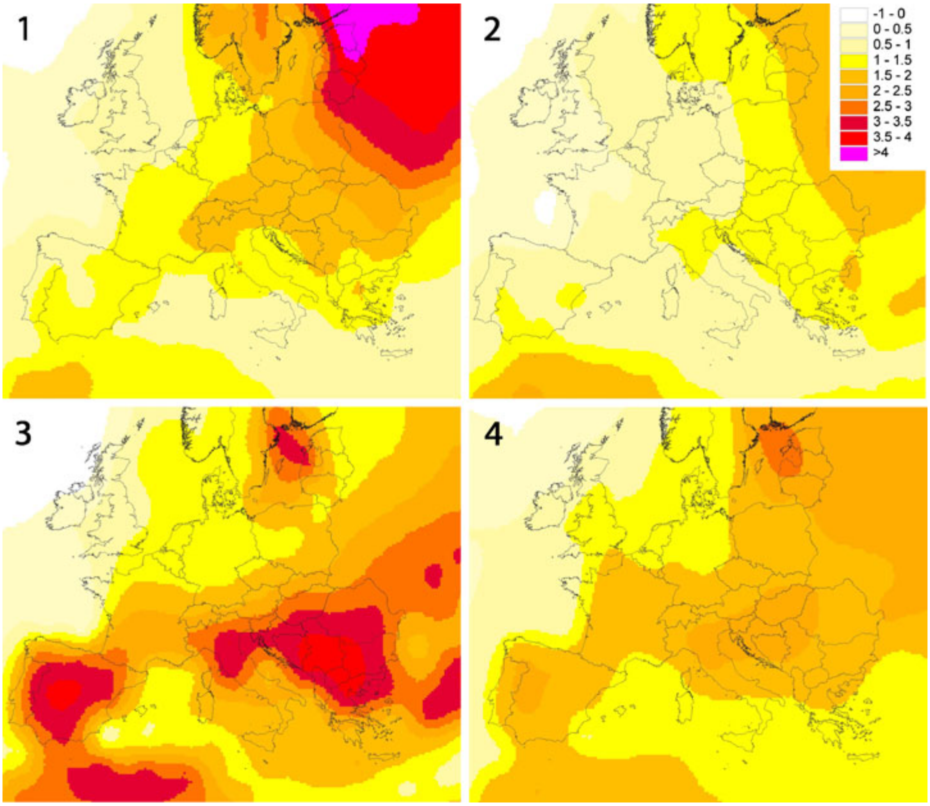

Fig. 4 Average seasonal change in temperature (°C) simulated by HadCM3 for the period 2030–2060 with respect to the relevant baseline 1975–2005. Legend: 1=winter (DJF); 2=spring (MAM); 3=summer (JJA); 4=autumn (SON)

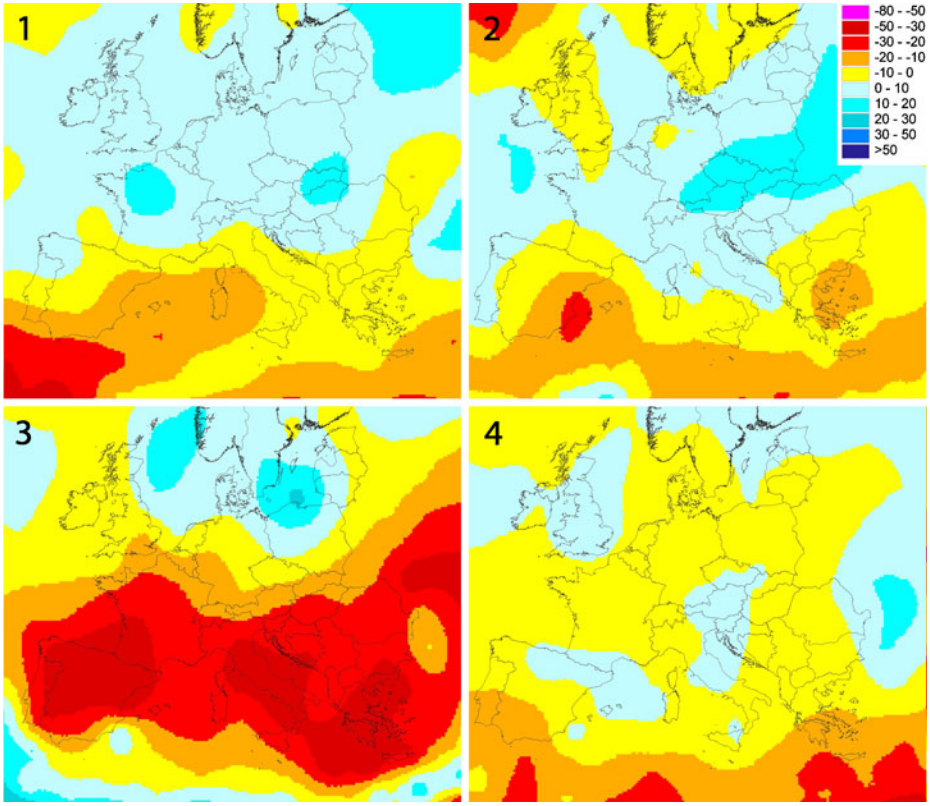

Fig. 5 Average seasonal change in rainfall (%) simulated by HadCM3 for the period 2030–2060 with respect to the relevant baseline 1975–2005. Legend: 1=winter (DJF); 2=spring (MAM); 3=summer (JJA); 4=autumn (SON)

In general, higher temperatures resulted in an advanced emergence, anthesis and maturation stages and in a shortening of growth cycle for both winter and summer crops. In particular, the duration of the crop-growth cycle decreased, in average, by 7%, 9%, 5% and 3% respectively for sunflower, soybean, spring and durum wheat over the entire EU domain.

Despite the shorter time for biomass accumulation, the Northern regions (above of 55° Lat N) experienced some beneficial effects of climatic change in terms of increased crop yield for sunflower (+8%) and spring wheat (+7%) whereas soybean was slightly negatively affected (−4%) (Fig. 6). This positive effect was the consequence of a higher rainfall rate combined with an increased RUE and WUE (induced by higher CO_2 concentration) and only a moderate increase in heat stress events at anthesis (+3%). Over these areas, the average value of the ratio of actual to potential evapotranspiration, (AET/PET), was generally higher with respect to the baseline period (+8%, in average) leading to a decrease in drought stress events during the reproductive stage (−15%, −5% and −17% for sunflower, soybean and spring wheat, respectively).

In contrast, in the southern areas, (below of 55° Lat N), yield of summer crops was reduced in the range of −5% (soft wheat and sunflower) to −13% (soybean). This was the result of generally higher water stress during the season and higher frequency of both heat

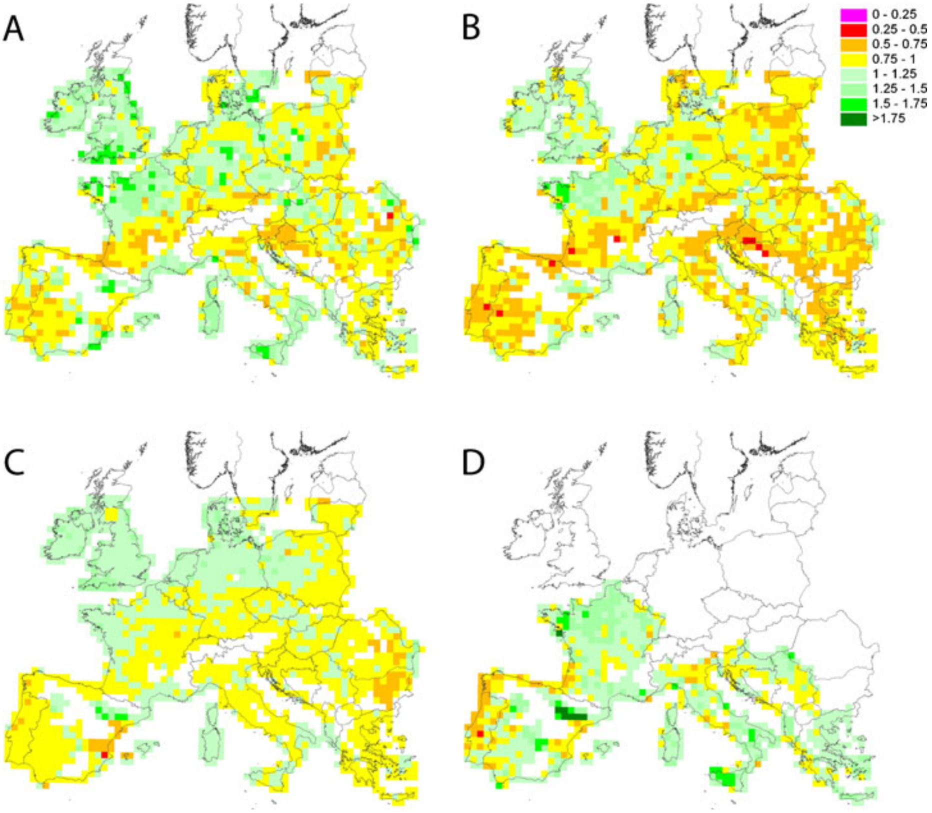

Fig. 6 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario with respect to the present period, not considering adaptation strategies

and drought stresses during at anthesis. ETa/ETp generally decreased (−7% for soybean, −4% for sunflower, no change for spring wheat) over this region and this resulted into a slight increase of drought stress event at anthesis, especially for sunflower and soybean, while no change was observed for spring wheat. On the other hand, heat stress frequency increased by 22%, 20%, 4.5%, for soybean, sunflower and spring wheat, respectively. In contrast, over the same regions, yield of durum wheat increased by 8% in average, as the joined effect of a shorter growth cycle and a crop growing season (i.e. autumn-winter) which exhibited no changes or even increase in rainfall with respect to the baseline (Fig. 5). This allowed the winter crop to escape the higher drought and heat stress frequency which are simulated by HadCM3 in summer. In particular, for durum wheat ETa/ETp remained unchanged, the frequency of drought stress during the reproductive stage decreased by 10%, while heat stress frequency slightly increased (+2%) with respect to the baseline.

Different adaptation options were implemented to test their effectiveness in reducing the negative impact of climate change as well as to exploit some advantages that climate change showed in some areas. The results for each adaptation option were compared to the relevant outputs as obtained in the BAU scenario.

3.4 Responses to adaptation options

3.4.1 Sowing time

As expected, an advanced sowing time resulted in advanced phenological stages with respect to BAU. Additionally, a general lengthening of the growing cycle for both winter and summer crops was observed. In contrast, a delayed sowing resulted in a general delaying of phenological stages and in a shortening of the time to maturity.

Both water stress and the impact of heat waves decreased for spring-summer crops as a consequence of an earlier sowing time and advanced phenological stages. While these effects were less evident for the northern regions, which were less exposed to higher temperatures and drought, in southern regions this strategy was most effective. The frequency of heat stress events was reduced by 8%, 9% and 3% respectively for sunflower, soybean and spring wheat. Additionally, the average ETa/ETp increased by 8%, 7% and 4%, with respect to BAU, resulting in a general decrease of drought stress events during anthesis and grain filling (−5% in average). This resulted in an increased yield for spring wheat (+17%), sunflower (+15%) and soybean (+13%) in the southern regions whereas the impact on the Northern areas was very limited (+2% in average) (Fig. 7, ABC). The beneficial impact of this strategy was less evident on durum wheat (Fig. 7, D). As mentioned above, the durum wheat growing cycle is already largely advanced with respect to spring-summer crops and this allowed a lower frequency of both heat and drought in BAU scenario. An advanced sowing time with respect to BAU only slightly decreased both water and heat stress, resulting in a +2% yield increase.

In contrast, a delayed sowing time, shifting plant growth where the frequency of drought and heat stress is higher (i.e. summer), resulted in a lower yield, with respect to BAU, for all the crops considered (Fig. 8). As expected, the spring-summer crops in southern regions experienced the higher decrease in yield (−18% in average) whereas the impact over the northern region was slightly lower (−15% in average). This was the result of a lower ETa/ETp (−8% for sunflower and soybean, −5% for spring wheat), corresponding to an increased drought stress frequency during the reproductive stage (+5% in average), as well as of a higher frequency of heat stress at anthesis (+10%, in average). In contrast, durum wheat yield was generally unaffected, except for southern regions, where a delayed sowing resulted in a −5% with respect to BAU.

3.4.2 Growth cycle length

The advanced development stages and the shorter growing period, as induced by the use of shorter growing cycle varieties, clearly reduced the frequency of both heat and water stresses for spring-summer crops especially in southern areas. Over these regions, the ETa/ETp increased, in average for all the crop types, by 10% resulting in a lower frequency of drought stress during the reproductive phases (−12% in average). The frequency of heat stresses dropped to −14% with respect to BAU. On the other hand, these beneficial effects were less evident in the northern regions, which in the future climate were less exposed to both drought and heat waves.

Despite the improved ETa/ETp ratio and the reduced impact of heat and drought stress events, the shorter growing season adversely affected yield accumulation of both winter and summer crops (Fig. 9). This was mostly evident in the northern areas where sunflower yield was reduced by 27%, soybean by 30%, and spring wheat by 36%. In contrast, in southern areas the

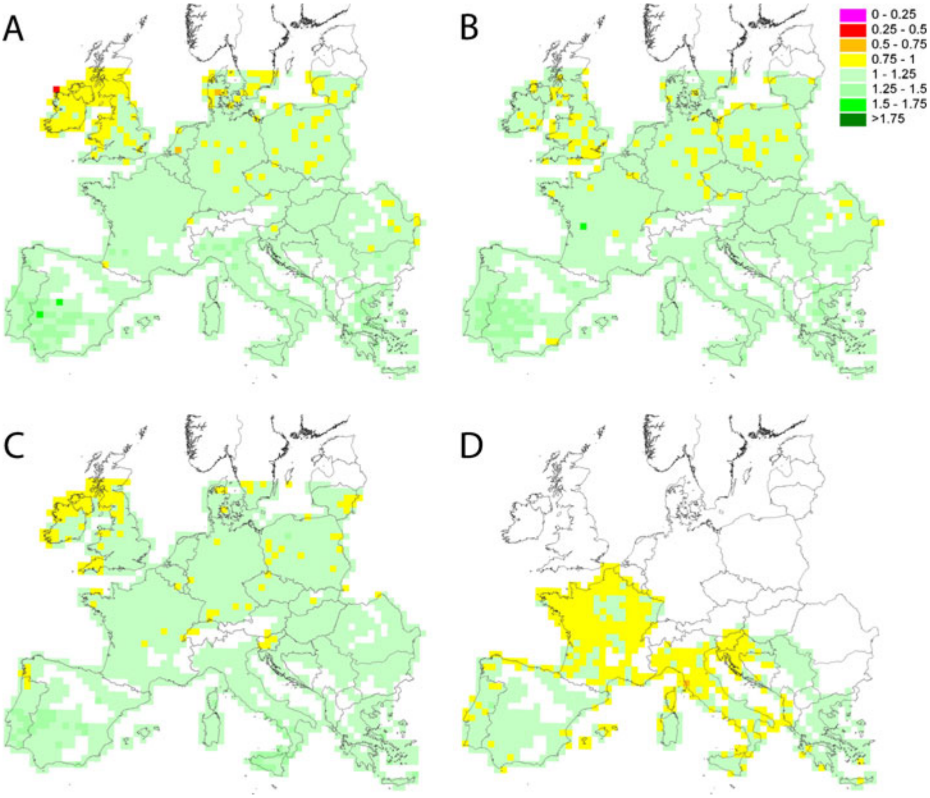

Fig. 7 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario considering an advanced sowing with respect to the present period. The relative change is calculated with respect to the same +2°C scenario without adaptation

impact was less effective, being the difference with the BAU scenario between −12% (soybean and sunflower) and −26% (spring and winter wheat).

In contrast, the use of longer cycle varieties generally resulted in an increased probability of both heat and drought stress, but the longer time for biomass accumulation ultimately resulted in a general increase of crop yield (Fig. 10). This effect was particularly evident in the northern areas, where crops were less exposed to both water and heat stress, even considering delayed phenological stages. Over these areas, both ETa/ETp and heat stress frequency were generally unaffected with respect to BAU so that the longer grain filling period was fully exploited for biomass accumulation. In particular both soybean and sunflower increased by 26% while the increase for spring wheat was even larger (+32%).

The beneficial effects of a longer growing season were less evident in the southern regions where sunflower yield increased in average by 7%, wheat spring by 12% and winter wheat by 17%, whereas soybean showed even a decreased yield with respect to BAU scenario (−9%) (Fig. 10). Over these areas ETa/ETp tended to decrease (in a range between −7% for spring wheat and soybean to −10% for winter wheat) resulting in a higher frequency of drought stress (+5% for soybean and sunflower, to +20% for spring and winter wheat). Additionally, the frequency of heat stress increased, on average, by 16% for the summer crops and by 5% for the winter crop.

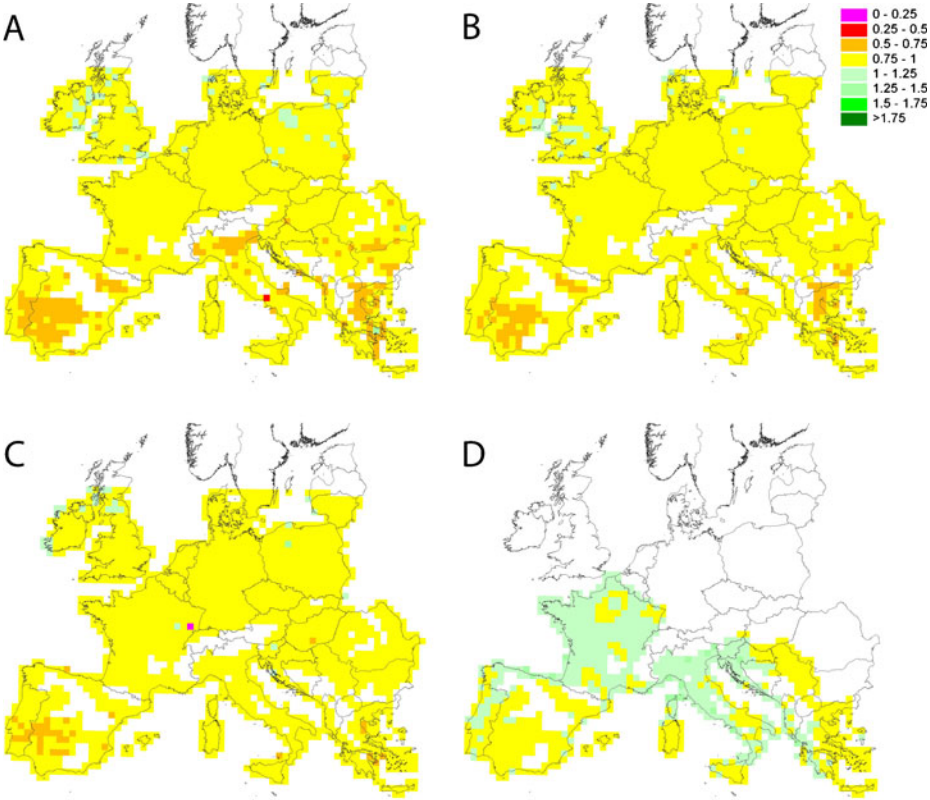

Fig. 8 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario considering a delayed sowing with respect to the present period. The relative change is calculated with respect to the same +2°C scenario without adaptation

3.4.3 Irrigation

The use of irrigation for rainfed crops reduced and overrode the negative impacts of climate change (for both winter and summer crops) determining a general increase of crop yield with respect to BAU scenario (Fig. 11).

The value of the ratio ETa/ETp increased generally over the entire domain, while the highest increases were observed over the southern regions for summer crops (+60% for sunflower, +35% for soybean and spring wheat). Only a slight increase was observed for the winter crop (+16%) over these areas. This trend corresponded to a decrease in drought stress during the reproductive stage for both summer and winter crops (−20% and −30%, respectively).

In contrast, ETa/ETp as well as the drought stress frequency during the reproductive stage in northern areas were the same as observed in BAU scenario.

Accordingly, the beneficial effects of irrigation were more evident in the southern Europe, as compared to the northern areas, and summer crops exhibited the larger increase in yield with respect to BAU. Over the Mediterranean basin, sunflower, soybean, and spring wheat yield increased, on average, by 100%, 35% and 41%, respectively, in response to an irrigation of 142, 70, and 120 mm ha^{-1} $season^{-1}$, respectively. For durum wheat the

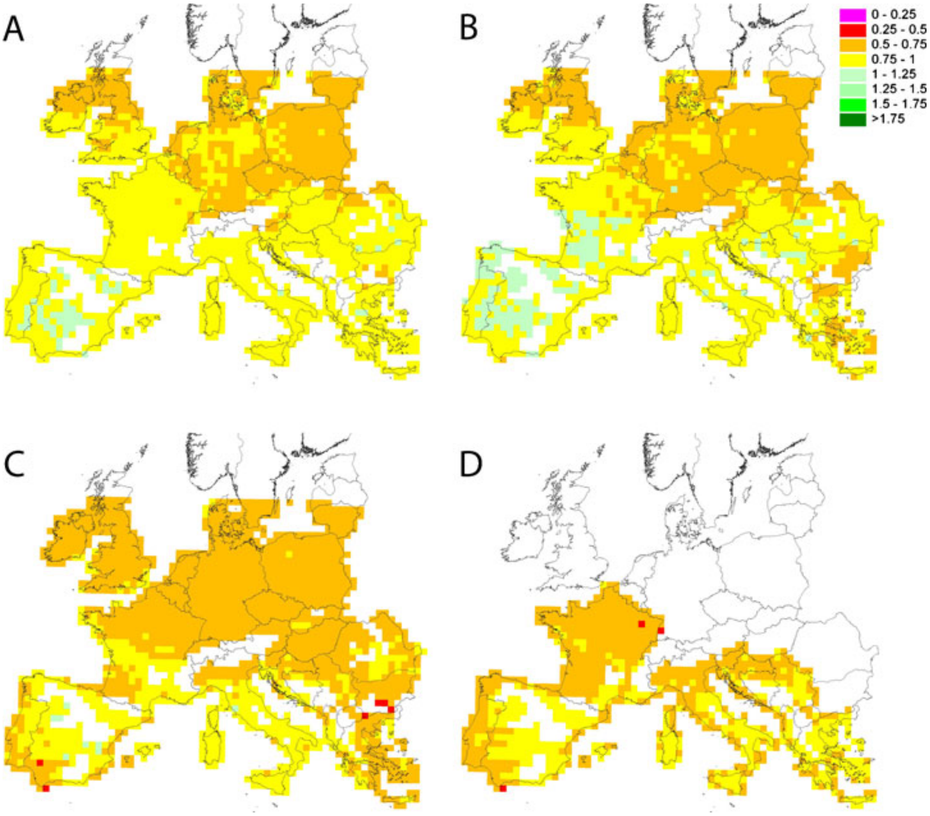

Fig. 9 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario considering the use of shorter cycle varieties with respect to the present period. The relative change is with respect to considering the same +2°C scenario without adaptation

increase of yield was less evident (+24%) which corresponded to 62 mm ha^{-1} $season^{-1}$. In northern Europe, sunflower yield increased by 60%, soybean by 27%, spring wheat by 15% corresponding to an irrigation of 76, 40 and 35 mm ha^{-1} $season^{-1}$, respectively.

4 Discussion

Agriculture inherently depends on climate conditions, and consequently is one of the most vulnerable sectors to the risks of global climate change. Adaptation to climate change is certainly an important component of any policy response in this sector and many studies have been performed to highlight the impact on crop yield and to propose possible strategies to cope with a changed climate (Iglesias and Minguez 1997: Matthews et al. 1997; Tubiello et al. 2000, 2002; Droogers 2004; Parry et al. 2004).

While most of these impact studies have considered only changes in average climate conditions, analyses of agricultural vulnerability indicate that the key attributes of climate change are those related to climatic variability, including the frequency of extreme weather conditions (Moriondo and Bindi 2006; Belliveau et al. 2006).

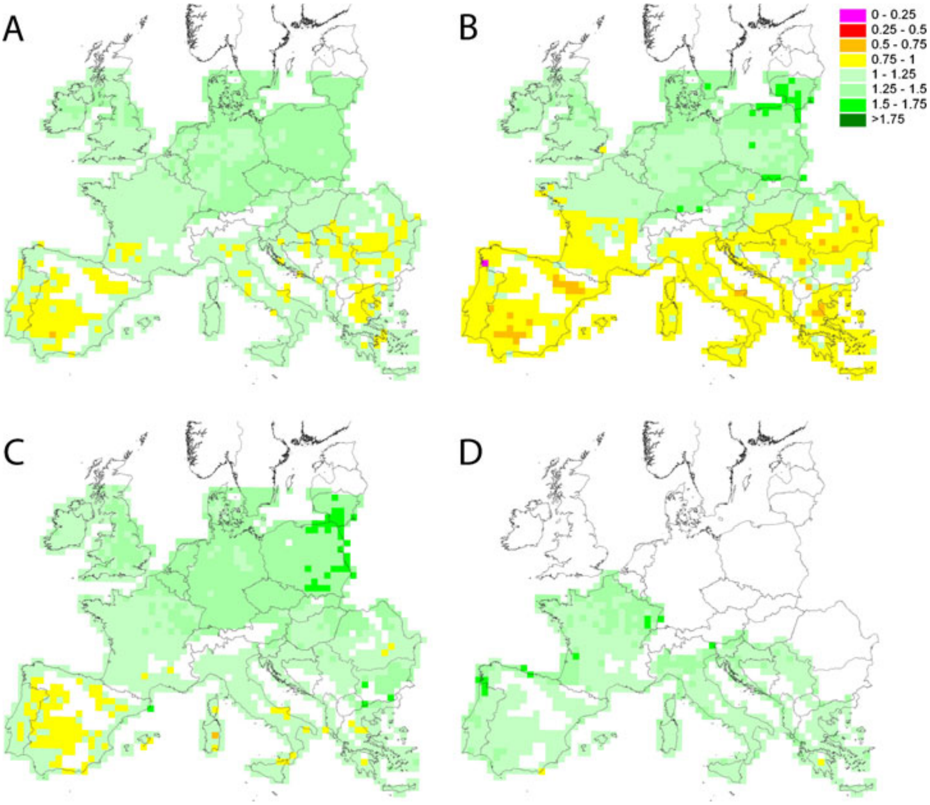

Fig. 10 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario considering the use of longer cycle varieties with respect to the present period. The relative change is calculated with respect to the same +2°C scenario without adaptation

Impact assessments are generally performed using the results of both empirical (statistical) and dynamic GCM downscaling. In the first case, the simple differences in temperature, rainfall and radiation between the baseline and future GCM runs is applied directly to the observed meteorological data in the relevant region to reproduce future climate (delta change approach). However in this case the future meteorological data do not incorporate changes in climatic variability, with the result that possible changes in climate extreme events are not simulated. In contrast, dynamic downscaling (i.e. RCM) makes it possible to simulate the change in both mean climate and climate variability with respect to the control period, as required for crop growth impact studies. However, as highlighted by, for example, Moberg and Jones (2004), given the existence of substantial biases in current RCMs, results based on future scenario integrations from these models should be treated with care.

In this study, the local calibration of a weather generator over observed gridded meteorological data and the following downscaling procedure ensured that simulation of future climate on a regional scale is reasonably trustworthy. In particular, the empirical downscaling performed by LARS WG considered the predicted changes in climatic mean and variability as derived from the GCM output. Additionally, the procedure proposed by Moriondo et al. (2010) was adopted for a reliable simulation of heat stress impact on crop

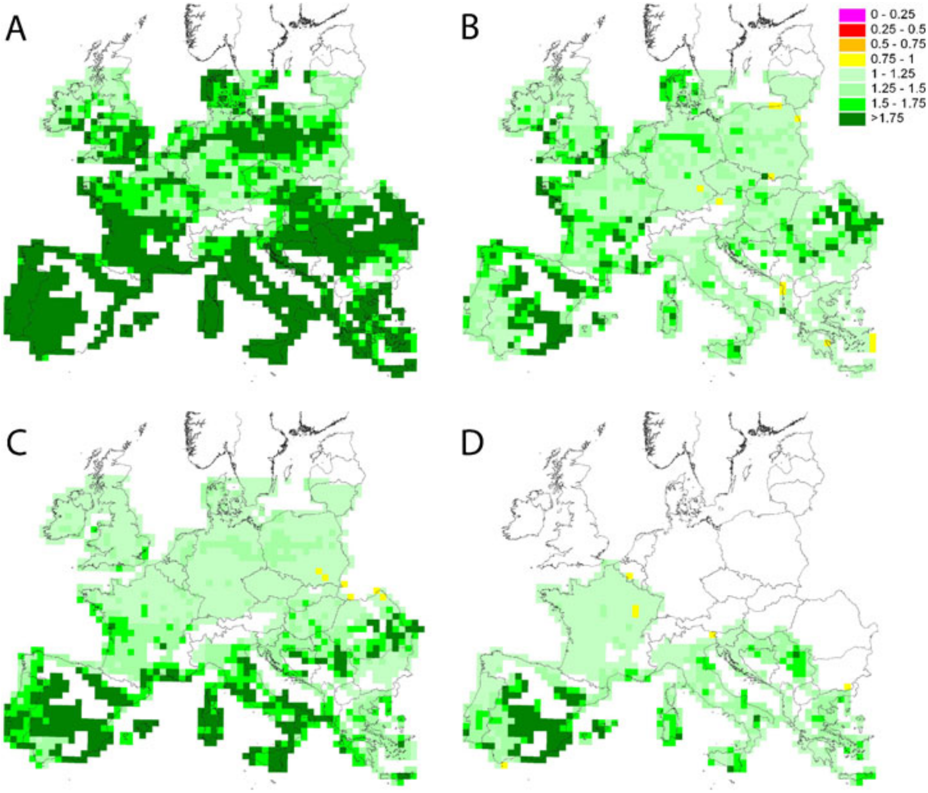

Fig. 11 Relative change in crop yield of sunflower (subfigure **a**), soybean (subfigure **b**), Spring wheat (subfigure **c**) and durum wheat (subfigure **d**) in a +2°C scenario considering the use of irrigation. The relative change is calculated with respect to the same +2°C scenario without adaptation

yield. Some limitations should be highlighted resulting from the assumptions adopted in this approach. In a few cases, synthetic data produced by LARS WG generator for the baseline, did not satisfactorily reproduce both average and extreme events frequency. This of course may result in a bias also for the future period. Additionally, both heat and water stress tolerance are species-dependent and different levels of tolerance may be identified within the same species. Accordingly, while these differences should be considered in an impact assessment, in this paper the results of a previous calibration performed over a low number of experiments was used.

Nevertheless, this paper indicated that the impact of climate change on EU agriculture depends on the relative magnitudes and effects of the mean and extreme event changes and that simple adaptation options may be adopted to reduce negative effects or exploit possible advantages of a warmer climate.

The general climatic picture depicted by HadCM3 in a +2°C scenario indicated that less summer precipitation, accompanied by growing temperatures, inevitably leads to more frequent and more intense droughts. Projections of precipitation change showed a marked contrast between winter and summer in Europe. Wetter winters are predicted throughout the continent, but in summer, there is a strong difference in projected precipitation change between Northern Europe getting wetter and Southern Europe becoming drier. However, there are large quantitative differences between scenarios and models. In general, the impact of a +2°C scenario depended on the counteracting effects among higher daily evapotranspiration rates, shortening of crop growth duration, and changes in precipitation patterns, as well as the effects of carbon dioxide on crop growth and water-use efficiency.

As a consequence, a +2°C scenario will have a higher impact on crops cultivated over the Mediterranean basin than on those cultivated in central and northern Europe. Increased temperature and heat stress frequency, accompanied by rainfall reduction and longer dry spells, were the main factors affecting crop yield over the Mediterranean basin in a BAU scenario. However the impact of heat stress events as well as lower rainfall may be either reduced or amplified depending on the crop growing season. In general, spring-summer crops were more subjected to the direct effect of heat stress at anthesis and drought during their growing cycle. This resulted in a severe yield loss. In contrast, winter crops, partially escaping the drought and heat stress of the summer period, exhibited a general increase in yield.

In contrast, the general increase in rainfall as projected by HadCM3 for latitudes above 55° N is expected to yield a general beneficial effect for both summer and winter crops over these areas.

It should be noted that the +2°C scenario for the time horizon 2100 is generally considered a very ambitious target. It will require very effective climate change mitigation (to curb the growth of atmospheric concentrations of greenhouse gases), undertaken from early on. If atmospheric concentrations of greenhouse gases grow in the business-as-usual mode, i.e. no effective mitigation is in place, commencing in the near future, the increase in average temperature by 2,100 is likely to be much higher, e.g. at the level of +4°C. The impacts in the agricultural sector in Europe will be considerably amplified in comparison with the +2°C scenario, and the adaptation needs will be much greater both in southern and northern Europe.

The adaptation options as proposed in this paper, reduced or amplified the impact of climate change on crop yield depending on the crop type and on the geographical area of their cultivation. In general, longer-growth-cycle varieties, increasing the time for biomass accumulation, resulted in a higher yield, as compared to BAU, for all the crops considered. However, this positive effect was more evident at the higher latitudes, where longer-cycle varieties were exposed neither to a summer drought, nor to higher frequency in heat stress with respect to BAU. By contrast, this positive effect was gradually reduced from North to South where summer crops, extending their growth cycle, were more exposed to higher summer temperatures and longer dry spell as simulated by HadCM3 over these areas. Winter crops, were, in any case, less affected by drought and heat stress event also in case of a longer season and their performances were generally better than in BAU also in the southern areas.

A shorter growth cycle resulted in a lower impact of both heat stress and drought on final yield. On the other hand, the lower time for biomass accumulation generally resulted in a decreased yield as compared to BAU, for all the considered crops.

At the higher latitudes the shifting of sowing dates had no impact on crop yield while the crops grown at the lower latitudes were very sensitive to this strategy. Over the Mediterranean basin, an advanced sowing time resulted in a successful strategy especially for summer crops, as already observed in Tubiello et al. (2000) and Moriondo et al. (2010). The advancement of anthesis and grain filling stages allowed the summer crops to partially escape the heat waves and drought. On the contrary, a delayed growing season resulted in an increased frequency of both heat stress and drought that highly reduced crop yield of summer crops. Changes in winter crops were less evident.

As expected, irrigation highly increased the yield of the selected crops, especially over the southern regions where water may be a limiting factor especially in summer period. In general, the amount of water required for maximizing the final yield increased progressively from north to south and irrigation requirements for summer crops were larger than for winter crops. Accordingly, the beneficial effects of this strategy were more evident for summer crops.

The cost associated with each strategy is variable and still unclear. For instance, while shifting the sowing dates for summer crops may be considered a successful no-cost option, a large shift probably would interfere with the agro-technological management of other crops, grown during the remainder of the year. This would cause an indirect cost that is in any case difficult to assess.

Switching from varieties with a longer growing season projected an additional increase of final yield under a warmer climate, especially in Northern Europe. While large variability in the length of crop growing season already exists, the development of new crop hybrids that may better match the changing climate, are considered a promising adaptation strategy, but the cost of these innovations is still unclear (Alexandrov and Hoogenboom 2000).

The use of irrigation to tackle summer water stress in southern Europe include a number of structural adaptations for enhancing water storage via increasing storage capacity for surface water (construction of retention reservoirs and dams), and groundwater (aquifer recharge); rainwater harvesting and storage; conjunctive use of surface water and groundwater; water transfer; desalination of sea water; removing of invasive non-native vegetation; and deep well pumping (Kundzewicz et al. 2007). The associated costs are difficult to be quantified, and a specific cost-benefit analisys should be performed.

However, seeking savings ("negaliters") rather than supply extension ("megaliters") is increasingly emphasized, e.g. via promotion of more effective water use; reduction of water losses, and increase of water saving. Improving efficiency of water use in irrigation (slogan "more crop per drop") is particularly important since irrigated agriculture is, globally, the main water user, in volumetric terms. Possible measures include: changes of agrotechnical practices (to minimize the loss of soil moisture; use of crop rotation, shifting sowing dates) and introduction of new cultivars (drought-tolerant crops). Soil moisture should be conserved e.g. through mulching.

5 Conclusions

This work aimed to assess the impact of a changing climate on agricultural yield in Europe, corresponding to a global warming of +2°C, considering possible changes in mean climate as well as in climate variability.

In particular, our results indicated that while in the present period agriculture in the northern Europe has been temperature-restricted, in the south it has been water-restricted. Projections for the future are good news for the North, where growing temperature relaxes former restrictions, but are not good news for the South, where a decrease in available water (due to both a decrease in precipitation and an increase in temperature) is likely. In countries of Central Europe, such as Poland, future conditions are expected to be more advantageous for sunflower and spring wheat.

Simple, no-cost adaptation options (advancement of sowing dates) may be implemented to tackle the expected change is southern Europe as well as to exploit possible advantages in the northern. The framework we set up for impact assessment was able to identify in which ways and which areas, some beneficial effects of climate change may be exploited (i.e. longer-cycle variety where wetter conditions are expected in a +2°C climate change) as well as the negative impact may be reduced (i.e. advancing sowing time for crops grown in the Mediterranean basin).

References

Adams RM, McCarl BA, Mearns LO (2003) The effects of spatial scale of climate scenarios on economic assessments: an example from U.S. Agriculture. Clim Change 60:131–148

Adger WN, Agrawala S, Mirza MMQ, Conde C, O'Brien K, Pulhin J, Pulwarty R, Smit B, Takahashi K (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 717–743

Alexandrov V, Hoogenboom G (2000) The impact of climate variability and change on crop yield in Bulgaria. Agric For Meteorol 1044:315–327

Alexandrov V, Eitzinger J, Cajic V, Oberforster M (2002) Potential impact of climate change on selected agricultural crops in northeastern Austria. Glob Chang Biol 8:372–389

Belliveau S, Smit B, Bradshaw B (2006) Multiple exposures and dynamic vulnerability: evidence from the grape industry in the Okanagan Valley, Canada. Glob Environ Change 16:364–378

Beniston M, Stephenson D, Christensen O, Ferro C, Frei C, Goyette S, Halsnaes K, Holt T, Jylha K, Koffi B, Palutikof J, Scholl R, Semmler T, Woth K (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Change 81:71–95

Butt AT, McCarl BA, Angerer J, Dyke PT, Stuth JW (2005) The economic and food security implications of climate change. Clim Change 68:355–378

Challinor AJ, Wheeler TR, Slingo JM (2005) Simulation of the impact of high temperature stress on the yield of an annual crop. Agric For Meteorol 135:180–189

Chimenti CA, Hall AJ (2001) Grain number responses to temperature during floret differentiation in sunflower. Field Crops Res 72:177–184

Droogers P (2004) Adaptation to climate change to enhance food security and preserve environmental quality: example for Southern Sri Lanka. Agric Water Manag 66:15–33

EC (2007) European Research on Climate Change. Projects of the Sixth Framework Programme. http://ec.europa.eu/research/environment/pdf/european-research-on-climate-change-fp6_en.pdf

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2°C global warming. Glob Planet Change 68:209–224

Hanson CE, Palutikof JP, Livermore MTJ, Barring L, Bindi M, Corte-Real J, Durao R, Giannakopoulos C, Good P, Holt T, Kundzewicz Z, Leckebusch G, Moriondo M, Radziejewski M, Santos J, Schlyter P, Schwarb M, Stjernquist I, Ulbrich U (2007) Modelling the impact of climate extremes: an overview of the MICE Project. Clim Change 81:163–177

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M (2007) Adapting agriculture to climate change. PNAS 104:19691–19696

Hulme M, Barrow EM, Arnell NW, Harrison PA, Johns TC, Downing TE (1999) Relative impacts of human-induced climate change and natural climate variability. Nature 397:688–691

Iglesias A, Minguez MI (1997) Modeling crop-climate interaction in Spain: vulnerability and adaptation of different agricultural systems to climate change. Mitig Adapt Strat Glob Change 1:273–288

IPCC (2007) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Kundzewicz ZW, Mata LJ, Arnell N, Döll P, Kabat P, Jiménez B, Miller K, Oki T, Şen Z, Shiklomanov I (2007) Freshwater resources and their management. In: Parry ML, Canziani OF, Palutikof JP, Hanson CE, van der Linden PJ (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Matthews RB, Kropff MJ, Horie T, Bachelet D (1997) Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agric Syst 54:399–425

Mearns LO, Katz RW, Schneider H (1984) Extreme high temperature events: changes in their probabilities with changes in mean temperature. J Clim Appl Meteorol 23:1601–1613

Mizina SV, Smith JB, Gossen E, Spiecker KF, Witkowski SL (1999) An evaluation of adaptation options for climate change impacts on agriculture in Kazakhstan. Mitig Adapt Strat Glob Change 4:25–41

Moberg A, Jones PD (2004) Regional climate model simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data 1961–1990. Clim Dyn 23:695–715

Moriondo M, Bindi M (2006) Comparison of temperatures simulated by GCMs, RCMs and statistical downscaling: potential application in studies of future crop development. Clim Res 30:149–160

Moriondo M, Bindi M, Sinclair TR (2005) Analysis of Solanaceae species harvest-organ growth by linear increase in harvest index and harvest–organ growth rate. J Am Soc Hortic Sci 130:799–805

Moriondo M, Giannakopoulos C, Bindi M (2010) The role of climate extremes in crop yield climate change impact assessments. Accepted for publication in Clim Change

Narciso G, Ragni P, Venturi A (1992) Agrometeorological aspects of crops in Italy, Spain and Greece. Joint Research Centre, Commission of the European Communities, Brussels, Luxembourg

New M (2005) Arctic climate change with a 2°C global warming. In: Rosentrater LD, New M, Kaplan JO, Comiso JC, Watt-Cloutier S et al (eds) Evidence and implications of dangerous climate change in the arctic. WWF International Arctic Program, Oslo, pp 1–15

Nordhaus WD (1991) To slow or not to slow: the economics of the greenhouse effect. Econ J 101:920–937

Olesen JE, Bindi M (2004) Agricultural impacts and adaptations to climate change in Europe. Farm Pol J 1:36–46

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob Environ Change 14:53–67

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. Clim Dyn 16:123–146

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10:23–36

Reilly J (1995) Climate change and global agriculture: recent findings and issues. Am J Agric Econ 77:727–733

Reilly J, Schimmelpfennig D (1999) Agricultural impact assessment, vulnerability, and the scope for adaptation. Clim Change 43:745–788

Risbey J, Kandlikar M, Dowlatabadi H (1999) Scale, context, and decision making in agricultural adaptation to climate variability and change. Mitig Adapt Strat Glob Change 4:137–167

Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. Nature 367:133–138

Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P (2007) Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 79–131

Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427:332–336

Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F (2007) Assessing key vulnerabilities and the risk from climate change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 779–810

Semenov MA, Barrow EM (1997) Use of a stochastic weather generator in the development of climate change scenarios. Clim Change 35:397–414

Smit B, Skinner MW (2002) Adaptation options in agriculture to climate change: a typology. Mitig Adapt Strat Glob Change 7:85–114

Smit B, McNabb D, Smithers J (1996) Agricultural adaptation to climatic variation. Clim Change 33:7–29

Stockle CO, Donatelli M, Nelson R (2003) CropSyst, a cropping systems simulation model. Eur J Agron 18:289–307

Tashiro T, Wardlaw IF (1990) The effect of high temperature at different stages of ripening on grain set, grain weight and grain dimensions in the semi-dwarf wheat ‘Banks’. Ann Bot 65:51–61

Tubiello FN, Donatelli M, Rosenzweig C, Stockle CO (2000) Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. Eur J Agron 13:179–189

Tubiello FN, Rosenzweig C, Goldberg RA, Jagtap S, Jones JW (2002) Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: Wheat, potato, maize, and citrus. Clim Res 20:259–270

Wall E, Smit B (2005) Climate change adaptation in light of sustainable agriculture. J Sustain Agric 27:113–123

Wheaton EE, McIver DC (1999) A framework and key questions for adapting to climate variability and change. Mitig Adapt Strat Glob Change 4:215–225