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LETTER

Climate change impact and potential adaptation strategies under alternate realizations of climate scenarios for three major crops in Europe

Marcello Donatelli[1,3,5], Amit Kumar Srivastava[2,3,5], Gregory Duveiller[3,4,5], Stefan Niemeyer[3] and Davide Fumagalli[3]

1   Council for Agricultural Research and Economics, CRA-CIN, Via di Corticella 133, 40128 Bologna, Italy
2   Institute of Crop Science and Resource Conservation, University of Bonn, Katzenburgweg 5, D-53115, Bonn, Germany
3   European Commission, Joint Research Centre (JRC), Institute for Environment and Sustainability (IES), Monitoring Agricultural Resources Unit, Via Enrico Fermi 2749, I-21027 Ispra (VA), Italy
4   European Commission, Joint Research Centre (JRC), Institute for Environment and Sustainability (IES), Climate Risk Management Unit, Via Enrico Fermi 2749, I-21027 Ispra (VA), Italy
5   Formerly at affiliation 3 during data processing.

E-mail: amit.srivastava@uni-bonn.de

Abstract

This study presents an estimate of the effects of climate variables and CO_2 on three major crops, namely wheat, rapeseed and sunflower, in EU27 Member States. We also investigated some technical adaptation options which could offset climate change impacts. The time-slices 2000, 2020 and 2030 were chosen to represent the baseline and future climate, respectively. Furthermore, two realizations within the A1B emission scenario proposed by the Special Report on Emissions Scenarios (SRES), from the ECHAM5 and HadCM3 GCM, were selected. A time series of 30 years for each GCM and time slice were used as input weather data for simulation. The time series were generated with a stochastic weather generator trained over GCM-RCM time series (downscaled simulations from the ENSEMBLES project which were statistically bias-corrected prior to the use of the weather generator). GCM-RCM simulations differed primarily for rainfall patterns across Europe, whereas the temperature increase was similar in the time horizons considered. Simulations based on the model CropSyst v. 3 were used to estimate crop responses; CropSyst was re-implemented in the modelling framework BioMA. The results presented in this paper refer to abstraction of crop growth with respect to its production system, and consider growth as limited by weather and soil water. How crop growth responds to CO_2 concentrations; pests, diseases, and nutrients limitations were not accounted for in simulations. The results show primarily that different realization of the emission scenario lead to noticeably different crop performance projections in the same time slice. Simple adaptation techniques such as changing sowing dates and the use of different varieties, the latter in terms of duration of the crop cycle, may be effective in alleviating the adverse effects of climate change in most areas, although response to best adaptation (within the techniques tested) differed across crops. Although a negative impact of climate scenarios is evident in most areas, the combination of rainfall patterns and increased photosynthesis efficiency due to CO_2 concentrations showed possible improvements of production patterns in some areas, including Southern Europe. The uncertainty deriving from GCM realizations with respect to rainfall suggests that articulated and detailed testing of adaptation techniques would be redundant. Using ensemble simulations would allow for the identification of areas where adaptation, like those simulated, may be run autonomously by farmers, hence not requiring specific intervention in terms of support policies.

1. Introduction

Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors which do include the agricultural sector as per the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2014). There is a wide range of processes through which climate change could potentially impact global scale agriculture (IPCC 2014). Due to the complexity of governing the interactions between these processes and the uncertainty associated with modelling them, it is not currently possible to reliably quantify the aggregate impacts of climate change on global-scale agricultural productivity (Gornall *et al* 2010), although actions have started as in the AgMIP—Agriculture Model Intercomparison and improvement Project. Some of these contrasting effects are mentioned by Jaggard *et al* (2010); for instance, the rise in CO_2 is expected to increase yields of C3 crops by about 13% but the higher ozone (O_3) concentration will reduce yields by 5% or more. CO_2 enrichment will reduce water consumption since leaf stomata will not have to be open as much, but this will be outbalanced by higher temperatures, which will increase evaporation rates. The beneficial advantages of CO_2 enrichments will also heavily depend on the success of plant breeders to create varieties that exploit this added-value. In Europe, future impacts of climate change on agriculture are currently generalized by a northward movement of crop suitability, with increased productivity in Northern Europe and a decline in both productivity and suitability in Southern Europe (Olesen *et al* 2002, Maracchi *et al* 2005, Falloon and Betts 2010). However, it is also foreseen that there will be an increase in extreme events, such as the heat waves over Europe of 2003 and 2010 (Schar *et al* 2004, Barriopedro *et al* 2011). These shifts and changes will offer opportunities and challenges requiring adaptation of European agriculture to the changing environment. Most studies present potential impacts in time horizons (2050, 2090) which show clear signals in terms of projected surface temperature, also enabling impact discrimination of different emission scenarios. However, in order to implement appropriate policies, the EU requires tools adapted to spatially characterize the potential vulnerability of its agriculture based on future climate predictions in the short term.

The objective of this study was to make an impact assessment of climate change scenarios on potential productivity of three rain-fed crops, exploring different adaptation strategies due to climate change scenarios over EU27 Member States. The focus was on the comparison of climate impacts across Europe.

2. Materials and methods

Winter wheat (*Triticum aestivum* L.), rapeseed (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.) were considered in this study in order to analyse specific interactions between the changing climate and crops with different seasonal growth cycles. Two realizations of the A1B emission scenario proposed by the Special Report on Emissions Scenarios (SRES), and made available by the ENSEMBLES project, were used. The A1B scenario was chosen as one of the most impacting due to a rise in temperature; hence this evaluates the potential impact of one of the most critical possible future climates.

2.1. Database description

Weather data is the driving force in crop simulation. To run simulations for projected climate change scenarios, weather data must match the requirements of crop models (Donatelli *et al* 2011). A gridded data set was built, covering Europe with a resolution of 25×25 km (Donatelli *et al* 2012a). In this study the time-slices 2000, 2020 and 2030 were chosen to represent the baseline and future climate, respectively. With the aim of simulating 30 years of daily data for each combination time slice and GCM projection, input weather data were generated with the stochastic weather generator ClimGen (Stöckle *et al* 2001) trained over GCM-RCM simulations (downscaled simulation from the ENSEMBLES project which was statistically bias-corrected prior to the use of the weather generator). Wind and relative air humidity were re-used (the measured, interpolated data of 1993–2007 were copied to all time slices) from the MARS database. Finally, the variables reference evapotranspiration and vapour pressure deficit were computed.

Given the target of this analysis, specifically to evaluate possible adaptation with respect to current agriculture, the reference time slice of 2000 (based on daily data of 1993–2007) was chosen. The two realizations of the A1B emission scenario based on HadCM3 (Semenov *et al* 2014, Liu *et al* 2013) and ECHAM5 (Müller *et al* 2010) were selected. Therefore, given the 2 realizations, a total of 6 climate datasets were used for the crop simulations. The two realizations of the emission scenario A1B were compared to the baseline period 2000 data using the estimates available from the same scenarios of the same years. The reference weather data used to evaluate the skills of GCM at simulating historical weather were the CGMS (Crop Growth Monitoring System) weather database, and the ECMWF (European Centre for Medium range Weather Forecasting). Both A1B realizations satisfactorily matched (qualitatively) the reference data series based on observations (Donatelli *et al* 2012a).

Simulations were run on a 25×25 km grid that covers Europe in the Lambert Azimuthal Equal Area

projection. This grid is the same as the one used operationally to forecast yields with MCYFS (MARS Crop Yield Forecasting System). A detailed description of the dataset used and data are available upon request at http://Mars.jrc.ec.europa.eu/Mars/About-us/AGRI4 CAST/Data-distribution.

Atmospheric CO_2 concentration was set to 355 ppm for the baseline period 2000, and to 400 and 420 ppm in the A1B scenario for the 2020 and 2030 time windows, respectively.

2.2. Crop growth model

The CropSyst version 3 (Stöckle *et al* 2003) model was re-implemented in the platform BioMA—Biophysical Model Applications (Donatelli *et al* 2012b), an extensible software platform for developing and running biophysical models on generic spatial units, was used in this study to simulate crop development and yield under potential and water-limited conditions. Deployments of the platform, and its tools and components were used, as examples, to create weather datasets for biophysical simulation (Donatelli *et al* 2012a), to estimate the impact on crop production in Europe (Donatelli *et al* 2011), to simulate soil pathogens under climate change (Manici *et al* 2014), to simulate the survival of insects damaging maize under climate change (Maiorano *et al* 2013), to estimate crop suitability to environment (Confalonieri *et al* 2012), to perform modelling solutions comparison at sub-model level (Donatelli *et al* 2014), to develop a library of reusable models for crop development and growth (Stella *et al* 2014), to estimate fungal infections (Bregaglio *et al* 2013), to estimate agro-meteorological variables (Bregaglio *et al* 2011, Donatelli *et al* 2006), to estimate quality of agricultural products (Cappelli *et al* 2014). CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to evaluate the effects of different pedo-climatic and management conditions on crop growth. CropSyst has already been used for studies on climate change impact (e.g., Tubiello *et al* 2000). The model accounts for increasing atmospheric CO_2 concentration on crop water use efficiency (WUE) and radiation use efficiency (RUE). It has a simplified approach to simulating the impact of CO_2 concentration on plant growth (Tubiello *et al* 2007) requiring a limited number of parameters, hence it is adequate for a study like that discussed in this paper. The user can input management parameters such as sowing date, cultivar genetic coefficients (photoperiodic sensitivity, duration of grain filling, maximum LAI, etc), soil profile properties (soil texture, depth), fertilizer and irrigation management, tillage and atmospheric CO_2 concentration, etc The simulation of crop development is mainly based on the thermal time required to reach specific stages of development. Thermal time is calculated as growing degree-day (GDD, degree C day^{-1}) accumulated

throughout the growing season (from sowing to maturity). Average air temperatures above a base temperature and below a cut-off temperature are considered for GDD calculation. In the simulation of crop development other environmental aspects, such as day length, low temperature requirements, soil water content, were also taken into consideration. In particular, for winter wheat and rapeseed the exposure to low, non-freezing temperatures (vernalisation) is required to enter the reproductive stage. The core of the model is the determination of the biomass potential growth under optimal conditions (without water stress) based both on crop potential transpiration and crop intercepted photosynthetic active radiation. The potential growth is then corrected by water limitation, if any, and the actual daily biomass gain is thus determined. The simulated yield is obtained as a product of the actual total biomass accumulated at physiological maturity and the harvest index (HI = harvestable yield/aboveground biomass). Currently, there are ongoing studies comparing different simulation model under various conditions for some crops, within the AgMIP effort (e.g., Asseng *et al* 2013 for wheat) also for gridded data (Elliott *et al* 2015); in the near future the results of these studies will enable broadening of the modeling base for this type of study, although providing coverage of such large areas would demand considerable engineering efforts.

2.3. Model set-up

Actual simulation was done at the 25 km grid cell level, where weather data is available for a total of almost 20 000 grid cells; the consequent level of abstraction of the production system was high, but represented a possible comparison covering the whole area. A unique synthetic soil profile representing a loam soil with a useful rooting depth of 1.5 meters, hence with a good soil water retention capability in the soil profile was used for all simulations. To run regional calibration the study area (EU27 member states) was divided into a number of zones. These zones are the basic spatial units that were used in the calibration procedure. To carry out the calibration for wheat and rapeseed, the whole study area was divided into three latitudinal zones. A unique crop variety was assigned to each zone in terms of its temperature sum requirements; the phenology simulation was begun via fixed sowing dates per zone. The assumption following this methodology is discussed in the next section. For the studied crops, the CGMS (http://Mars.jrc.it/Mars/About-us/AGR I4CAST/Crop-yield-forecast/The-Crop-Growth-Mo nitoring-System-CGMS) crop calendar was used to set the current sowing dates in the simulations. As model calibration requires parameter adjustment within a reasonable range of fluctuation suggested by research experiments, expert opinion or background knowledge, few crop input parameters were calibrated (see table 1). These parameters were adjusted within a

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Table 1. Crop input parameters used in simulations: their values and source of information (C: calibrated; D: CropSyst default values; L: derived from literature). NE = Northern Europe; CE = Central Europe; SE = Southern Europe.

Parameter	Wheat Value			Rapeseed Value			Sunflower Value			Units	Source
	NE	CE	SE	NE	CE	SE	NE	CE	SE		
Thermal time accumulation											
Degree days emergence	300	300	300	125	230	230	94	94	94	°C- days	C
Degree days begin flowering	1100	1500	1700	800	900	900	1055	1055	1055	°C- days	C
Degree days begin grain filling	1200	1600	1800	900	1000	1000	1150	1150	1150	°C- days	C
Degree days physiological maturity	1600	2000	2200	1150	1300	1400	1600	1625	1677	°C- days	C
Base temperature (Tb)	0	0	0	6	6	6	6	6	6	°C	L
Cutoff temperature (Tcutoff)	20	20	20	30	30	30	30	30	30	°C	L
Phenologic sensitivity to water stress	0	0	0	0	0	0	0	0	0		D
Photoperiod											
Photoperiod simulation	Activated	Activated	Activated	Activated	Activated	Activated	Not Activated	Not Activated	Not Activated		
Day length photoperiod to inhibit flowering	10	10	10	10	10	10	0	0	0	h	L
Day length photoperiod for insensitivity	18	18	18	18	18	18	0	0	0	h	L
Morphology											
Specific leaf area (SLA)	21	22	20	21	22	20	20	20	20	$m^2 \, kg^{-1}$	C
Fraction of maximum LAI at physiological maturity	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		D
Maximum rooting depth	1.5	1.5	1.5	1.25	1.25	1.25	1.5	1.5	1.5	m	L
Leaf duration	1200	1600	1800	1000	1000	1000	1000	1000	1000	°C- days	C
Extinction coefficient for solar radiation (k)	0.48	0.48	0.48	0.45	0.45	0.45	0.5	0.5	0.5		L
ET crop coefficient at full canopy	1.18	1.18	1.18	1.18	1.18	1.18	1.15	1.15	1.15		L
Growth											
Photosynthetic pathway	C3			C3			C3				
Light to above ground biomass conversion (RUE)	3.1	3.5	3.5	3.1	3.5	3.5	2.88	2.88	2.88	$g \, MJ^{-1}$	L
Optimum mean daily temperature for growth (Topt)	19	19	19	20	20	20	20	20	20	°C	L
Aboveground biomass-transpiration coefficient (KBT)	5.8	5.8	5.8	6.7	6.7	6.7	4.9	4.9	4.9	$kPa \, kg \, kg^{-1}$	L
Maximum water uptake	9	9	9	12	12	12	12	12	12	$mm \, day^{-1}$	D

Table 2. Adaptation strategies. Adaptation tested via simulation are a factorial combination of the levels in the table.

Crop	Genotype	Planting	Irrigation
Wheat	2 levels (+1, standard); Shorter and longer maturity (about ±10 calendar days)	2 levels (+1, no delay); Delay of 10 and 20 calender days (fall sowing)	No
Rapeseed	2 levels (+1, standard); Shorter and longer maturity (about ±10 calendar days)	2 levels (+1, no delay); Delay of 10 and 20 calender days (fall sowing)	No
Sunflower	2 levels (+1, standard); Shorter and longer maturity (about 10 calendar days)	2 levels (+1, no anticipation); Anticipation of 10 and 20 calendar days (end of winter sowing)	No

narrow range given by the CropSyst User's manual (Stöckle and Nelson 1994), based on outputs of growth characteristics and minimizing the differences between reference (as available in the CGMS platform) and simulated yields. Other crop specific input parameters required to feed the model were extracted from the literature (see table 1). In this study, CropSyst was initially calibrated by using crop parameters for each of the defined zones from available literature values which were site particular; then phenology was corrected for regional differences based on based on the CGMS platform.

2.4. Crop simulation and adaptation strategies

Crop simulations for each crop and each climate change scenario with and without adaptation were performed and compared to the baseline results; results were then presented as percentage variation with respect to the reference (baseline) performance (yield averages over 30 years). The first 'without adaptation' set of results serves as a key benchmark, against which possible benefits of realized adaptation actions can be estimated for the future. The adaptation strategies (adaptation attempts) evaluated are examples of technical adaptations that farmers could presumably implement autonomously. In other terms, this type of adaptation could and would likely occur without any exogenous input, hence not requiring any support policy. Consequently, the interest of the type of adaptation evaluated is to identify the hotspots where the autonomous adaptation by farmers (with respect to water availability and air temperature) would likely not be able to cope with the change in climate. The results presented, for each cell, are the best average yields which may be due to an adaptation strategy or even due to the standard agricultural management of the baseline.

Sowing dates of selected crops were shifted by either bringing forward or delaying sowing by either 10 or 20 calendar days with respect to the baseline sowing date (S_0). The other factor which was considered as an adaptation technique was the length of the biological cycle; hence simulating varieties with both a shorter and a longer maturity time with respect to the reference—current average—varieties (see table 2). This was achieved by either decreasing or increasing the number of the crop parameters growing degree days in order to get a variation of flowering and

physiological maturity. No efficiency difference in genetically based grain production was considered, assuming that the time horizon of interest is too close to produce substantially improved varieties.

All combinations related to genotype and planting time were explored. Crops were simulated in cells where their relative occupancy resulted in 1% or greater of the agricultural area according to the JRC MARS crop masks used in the CGMS system (http://Marswiki.jrc.ec.europa.eu/agri4castwiki/index.php/Main_Page).

## 3. Results and discussion

3.1. Weather

The maps (figures 1 and 2) describe the differences in the characterization of cumulated precipitation and cumulated potential evapotranspiration in the 2020 and 2030 time horizon between the two models: HadCM3 and ECHAM5. Precipitation patterns change considerably comparing the two A1B realizations; noticeably, the difference in Southern Europe for rainfall, where water availability is absolutely critical for rain-fed crops, appears very important.

Changes in the precipitation regime are dominated by a strong increase in cumulated rain over a zone centred south of the Alps and extends to the entire Italian peninsula and the Balkans. Scandinavia and the British Isles also expect higher rainfall by 2020, especially in the summer. Whereas by 2030, in central and eastern Europe, drier weather is evident.

As for crop responses, this study has produced a substantial amount of results given the combination of crops, time horizons, yield levels and adaptation strategies tested.

3.2. Wheat

The overall expected situation of wheat yield is very different depending on whether the HadCM3 or the ECHAM5 realization of the A1B scenario is used. Figure 1 resumes the expected situation of water-limited wheat yields in 2020 according to the model used. The differences in spatial patterns of yield reflect the substantial differences in rainfall patterns between ECHAM5 and HadCM3 rainfall (Donatelli *et al* 2012a). The reason for an increase in yields in Southern Europe, besides when an increase in rainfall is estimated with HadCM3, is the shortening of the
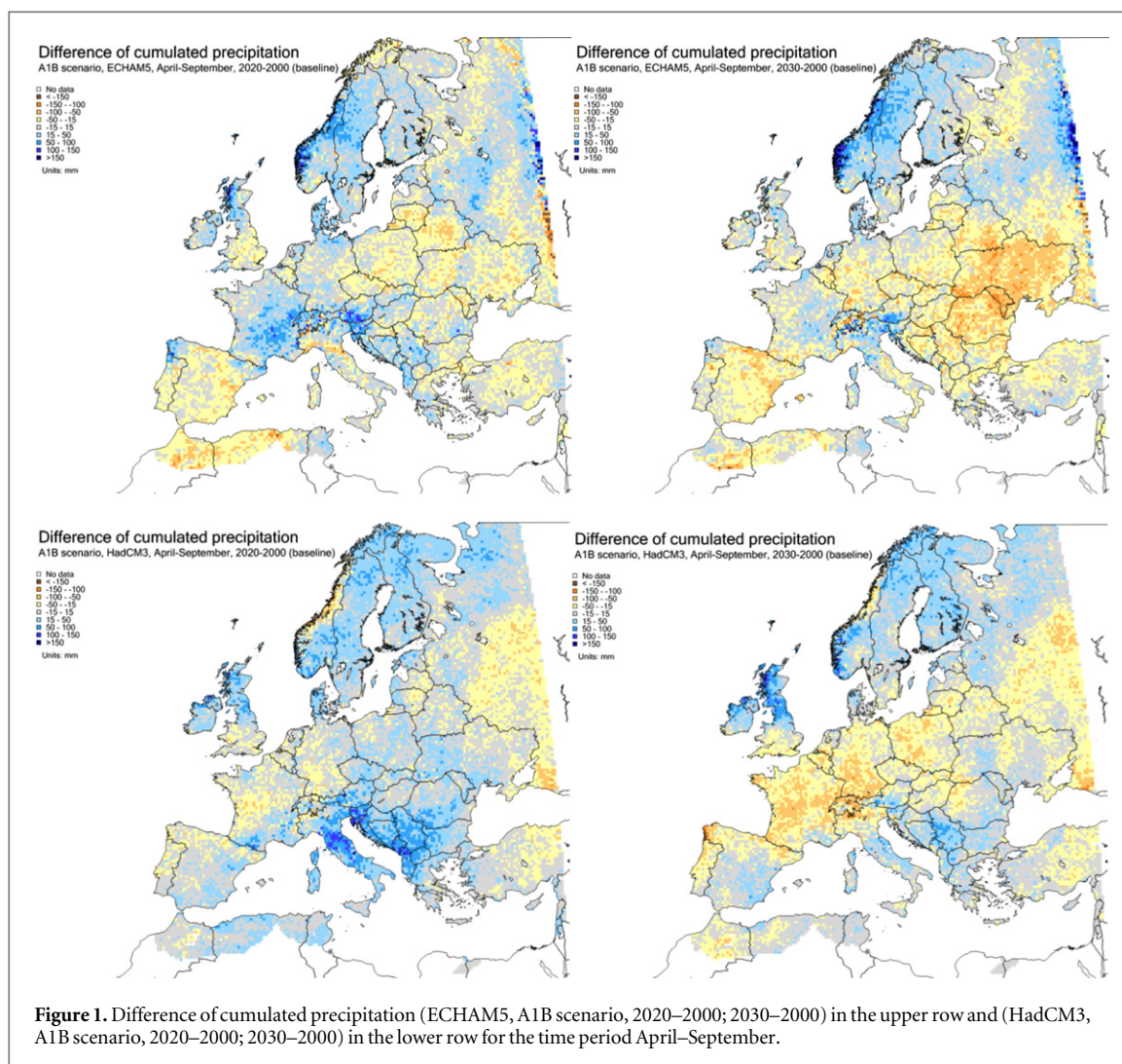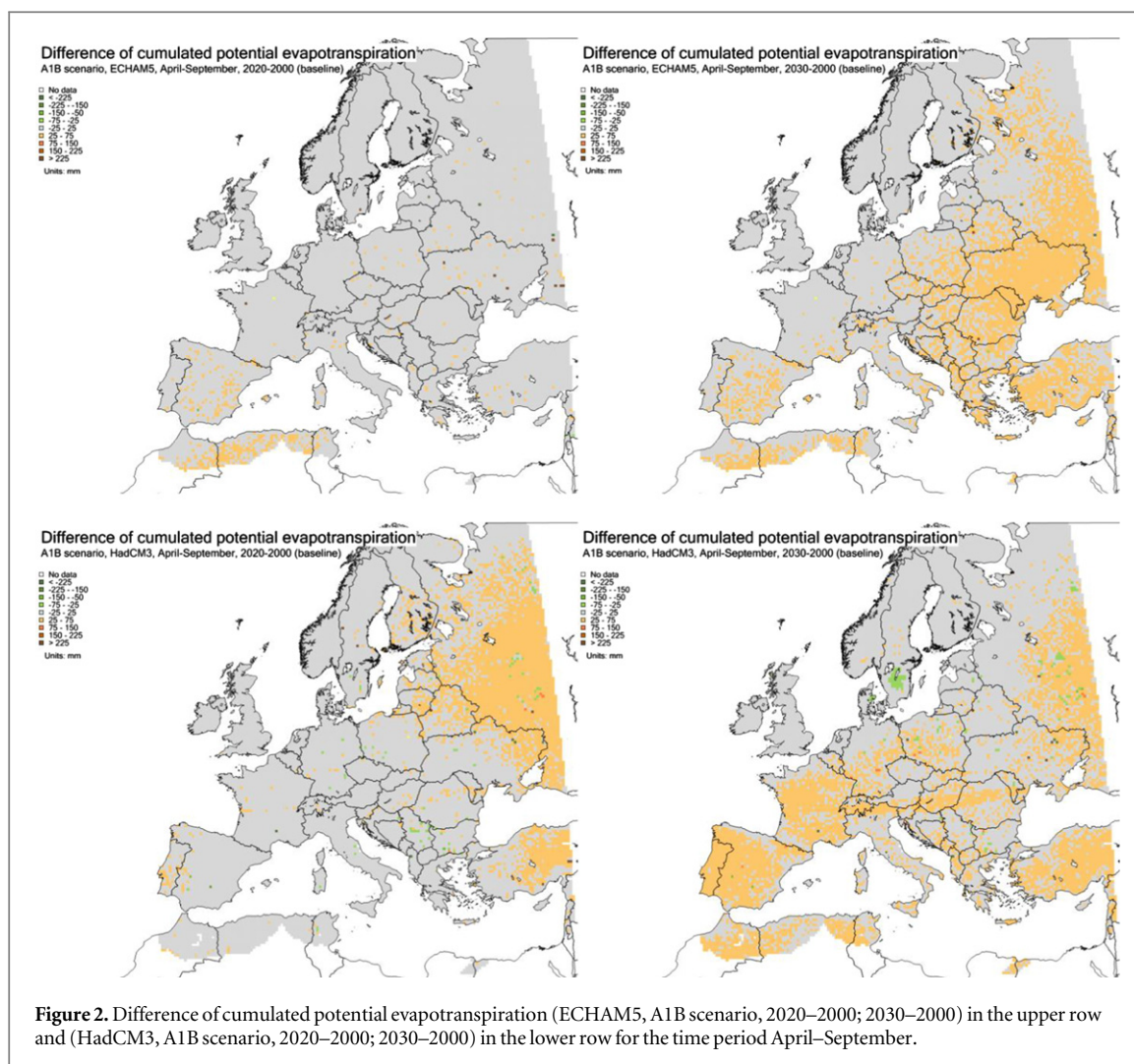
Figure 1. Difference of cumulated precipitation (ECHAM5, A1B scenario, 2020–2000; 2030–2000) in the upper row and (HadCM3, A1B scenario, 2020–2000; 2030–2000) in the lower row for the time period April–September.

crop cycle that may impact positively by improving the avoidance to summer water stress. This also may occur when comparing crop performance of 2020 versus 2030, for instance in Southern Spain, (with the ECHAM5 realization) where the estimated yields are slightly better in 2030 because of the better avoidance of summer water stress via a shorter growth cycle. The positive effect of avoidance of summer stress had already been observed via simulation with different GCM inputs at a location of Southern Italy (Donatelli *et al* 1998).

Ludwig and Asseng, (2010) and Van Ittersum *et al* (2003) in previous simulation studies have shown that in drier environments earlier flowering varieties often increase potential yield, therefore, in a warm and drying climate, it might be beneficial to develop earlier flowering varieties; while in a warming climate, later flowering varieties are likely to increase grain yield provided that sufficient soil moisture is available. In agreement with our results, Semenov *et al* (2014) postulated that in Southern Europe, agronomic practices such as the sowing date are used to ensure booting and flowering occur before drought is excessive. Balcovic *et al* (2014) who predicted an increase in wheat yields

by about 10–20% in North Europe by 2050 compared to baseline 2000. However, in this study our projection is by 2030. Carbon fertilization is also expected to contribute to the increase in yield given the current estimates of CO_2 concentrations in the near future, markedly higher than those in the first studies of crop growth simulations in future scenarios, performed in the 90s.

The results of the adaptation strategies (figure 3) show a general improvement across Europe, except for the Iberian Peninsula under the ECHAM5 realization, which suffers from excessive aridity. In general terms, the best yield is realized by delaying the wheat planting date by 10 days, and using a variety with a longer growth cycle. It must be noted, however, that the results do not account for a possible increase in plant disease pressure, as from wheat rusts, for instance. In the 2030 horizon, the same general conclusions can be drawn; only that due to a generalized increase in temperature, the yield increases with adaptation are slightly milder compared to 2020. An important outcome of the simulations under the HadCM3 scenario, which estimates an increase in rainfall, is that yields are expected to increase in Southern Europe even without

Figure 2. Difference of cumulated potential evapotranspiration (ECHAM5, A1B scenario, 2020–2000; 2030–2000) in the upper row and (HadCM3, A1B scenario, 2020–2000; 2030–2000) in the lower row for the time period April–September.

adaptation because of rainfall patterns and CO_2 fertilization.

The variability of yields from adapted agro-management was often larger than that of the baseline, even if adaptation alleviated the impact; in a smaller number of cases the variability decreased (figure 4, wheat). There is however no clear spatial pattern; the reasons for the variability should probably be investigated possibly to provide different techniques of adaptation that are more articulated than the basic ones tested (e.g. opportunistic sowing time or choice of varieties). The other two crops, rapeseed and sunflower, also show similar patterns of yield variability even if, overall, the increase of variability of sunflower resulted smaller than that of wheat (figure not shown).
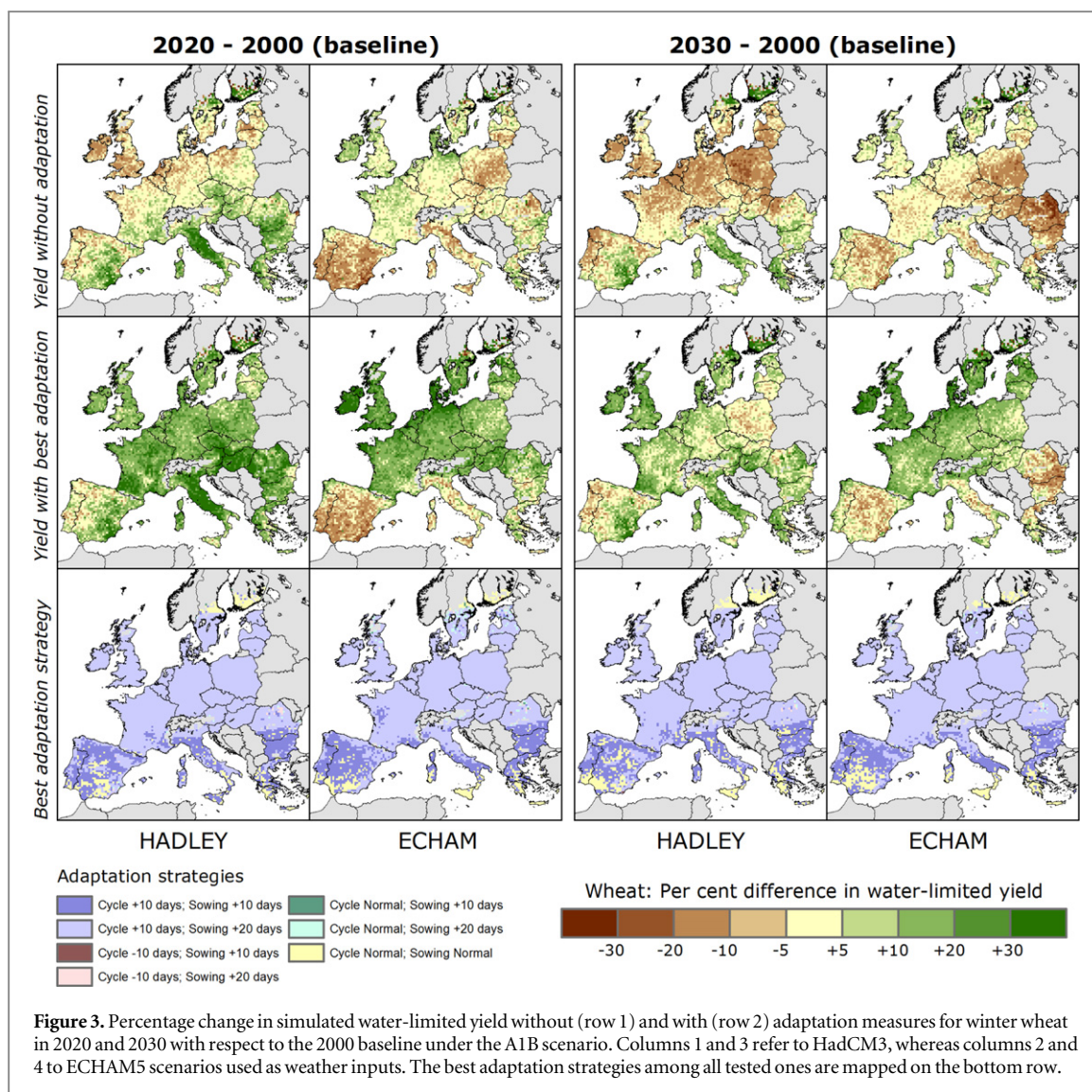
3.3. Rapeseed
There is an indication from the simulation results that by 2020, compared to the baseline 2000, water stress might be a concern in parts of France, Germany and UK as a decline of 5–30% in the rapeseed yield is anticipated which further worsens

in the 2030 time horizon. Whereas, by 2020 under the HadCM3 scenario yield improvements in parts of Spain, Italy, Southern France, Hungary and Romania, which without adaptation measures become less visible by 2030. This suggests, firstly, that water is not a limiting factor because of a higher amount of estimated precipitation and, secondly, the positive implication of CO_2 fertilization. Factors impacting on yield do not respond according to an additive model, and where there is no clear limiting factor like severe water shortage, system performance becomes difficult to explain by looking at driving force patterns and in fact requires simulation to be inclusive of key, non-linear responses, which have no analytical solution.

Simulated adaptation measures show promising results anticipating a yield increase that ranges from 10–30% in most parts of Europe with exceptionally higher yields in Poland, Hungary and Romania which are numerically more than 30% compared to baseline yields in the time window of 2020. However, by 2030 the improvement has become milder but still positive across the whole of Europe. The best adaptation

Figure 3. Percentage change in simulated water-limited yield without (row 1) and with (row 2) adaptation measures for winter wheat in 2020 and 2030 with respect to the 2000 baseline under the A1B scenario. Columns 1 and 3 refer to HadCM3, whereas columns 2 and 4 to ECHAM5 scenarios used as weather inputs. The best adaptation strategies among all tested ones are mapped on the bottom row.

strategy was very similar to that of wheat, i.e., longer maturity genotypes and delaying planting (see figure 5).
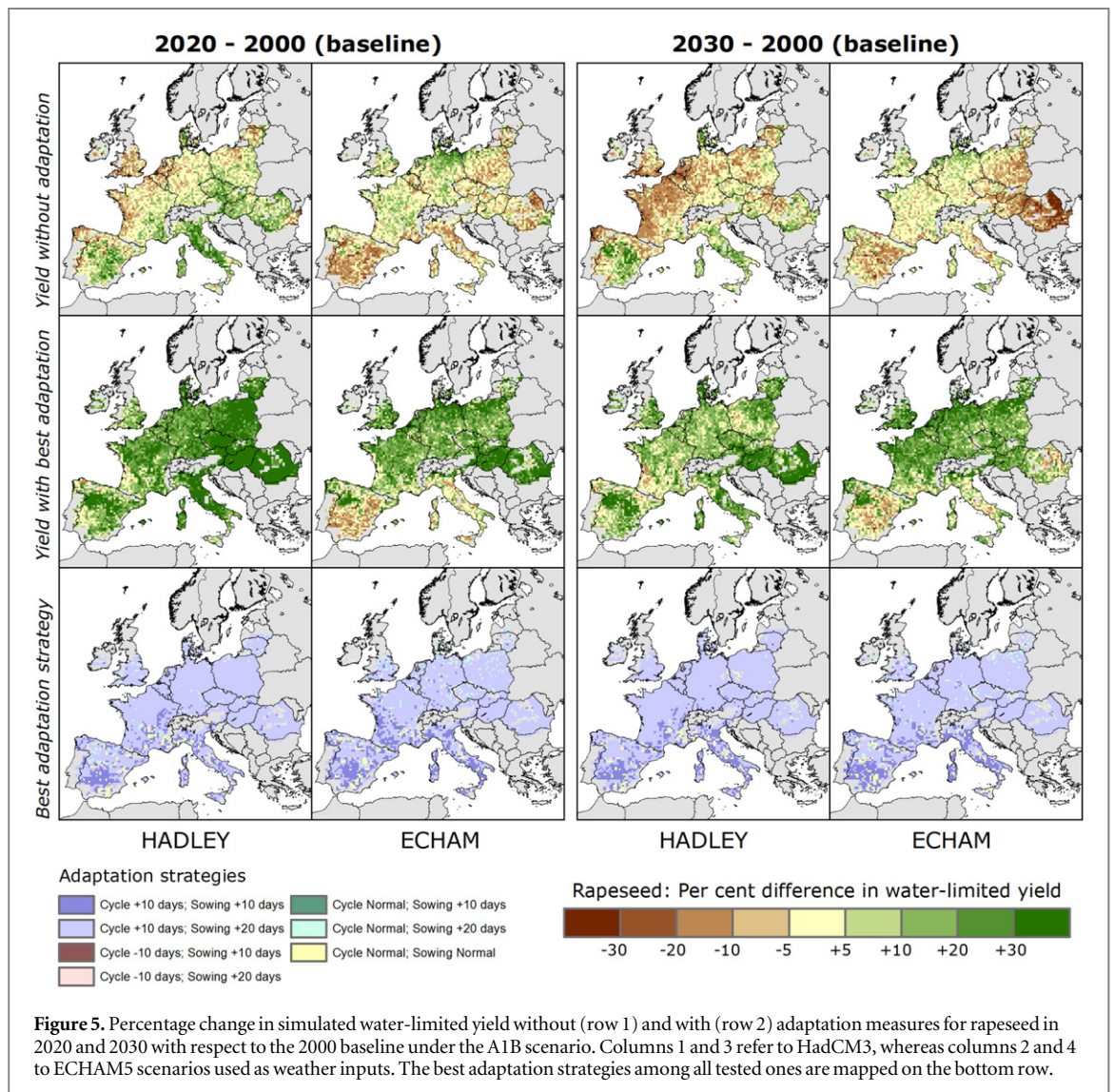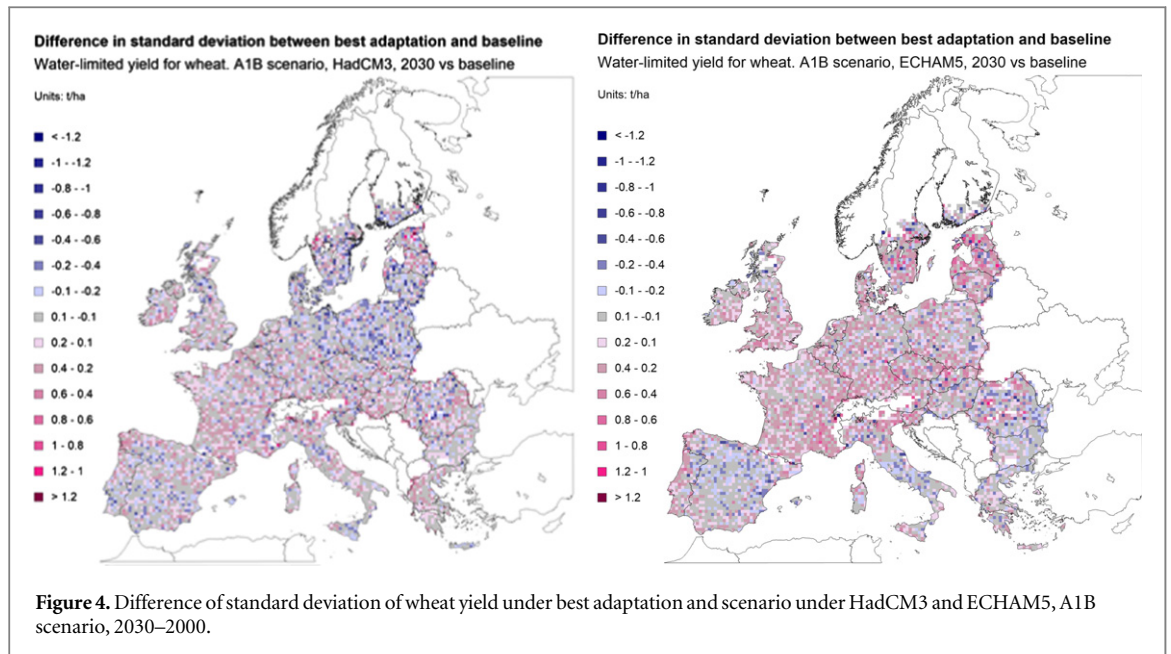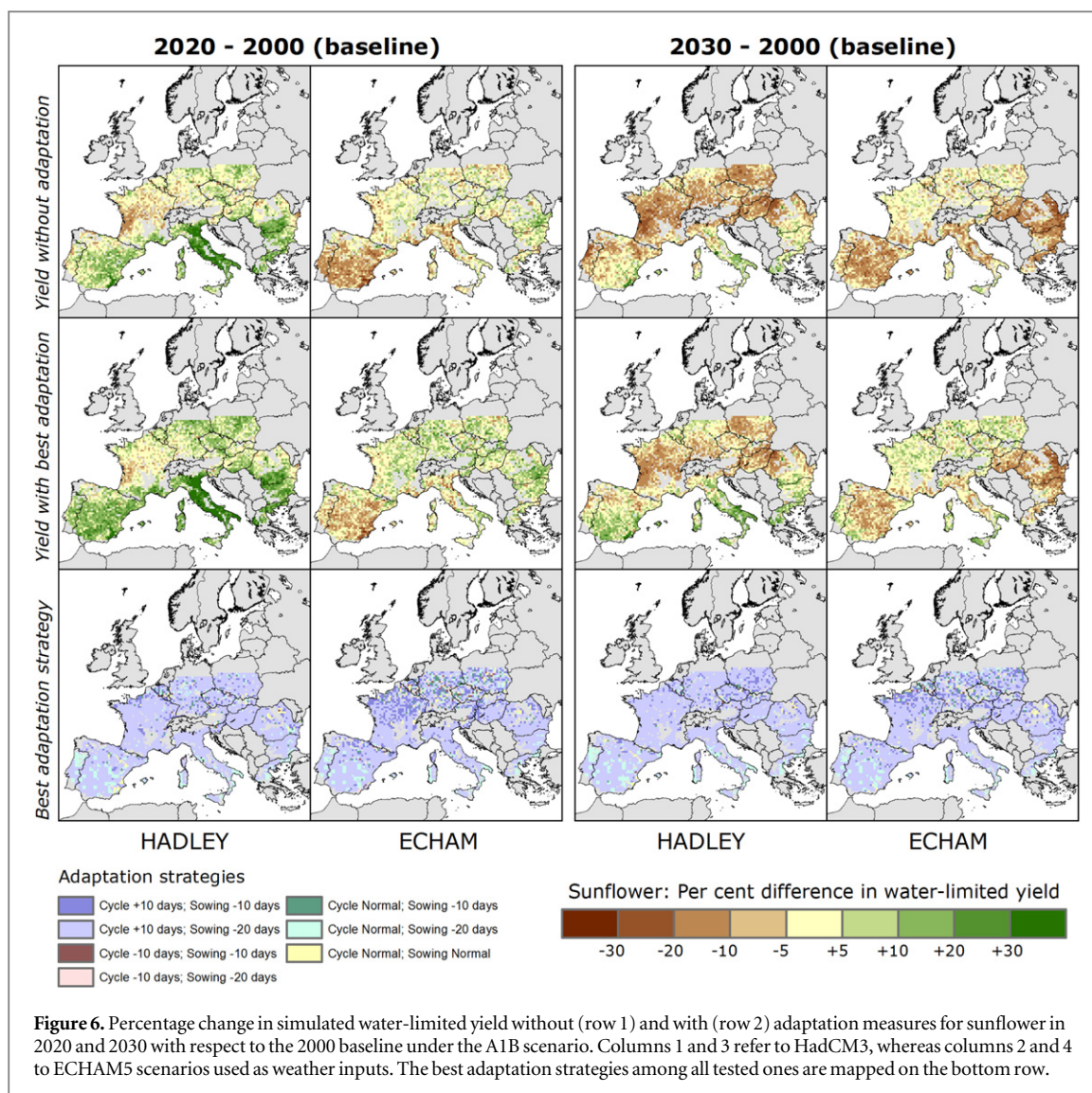
3.4. Sunflower

The results show an improvement (HadCM3) in sunflower yield in Spain, Italy, Romania and Bulgaria (in general areas at southern latitudes) with some patches of decline in France and Germany in 2020, compared to the baseline time horizon. The improvements can be directly linked to the higher precipitation compared to baseline. By 2030 the improvements get milder in Southern European countries, and countries in Eastern Europe see 10–30% yield decline. Adaptation for sunflower was not completely effective under the 2030 time horizon especially in the northern part of Europe whereas a 10–20% improvement can be foreseen under the ECHAM5 realization, sporadic situations are observed under HadleyCM3 (figure 6).

4. Assumptions

The final report of the AVEMAC project (Donatelli *et al* 2011) includes an articulated discussion about the assumptions working at the level of abstraction of this study, and clarified that analyses like those explored in this paper highlight potential hotspots, for which a more articulated, input data-rich analysis, should be run. For this reason, although the general impact trends that were computed can be considered robust in terms of extensive regional signals across all three crop types simulated, specific crop-country results need to be interpreted with caution since they are highly dependent on specific cultivars represented by model parameters in the simulations, which also ignore possible nutrient limitations.

Among the assumptions made in the simulation study, model calibration was carried out based on literature review only, which generally makes reference data available for large areas. Hence this study can be significantly refined by interacting with local experts,

Figure 4. Difference of standard deviation of wheat yield under best adaptation and scenario under HadCM3 and ECHAM5, A1B scenario, 2030–2000.

Figure 5. Percentage change in simulated water-limited yield without (row 1) and with (row 2) adaptation measures for rapeseed in 2020 and 2030 with respect to the 2000 baseline under the A1B scenario. Columns 1 and 3 refer to HadCM3, whereas columns 2 and 4 to ECHAM5 scenarios used as weather inputs. The best adaptation strategies among all tested ones are mapped on the bottom row.

Figure 6. Percentage change in simulated water-limited yield without (row 1) and with (row 2) adaptation measures for sunflower in 2020 and 2030 with respect to the 2000 baseline under the A1B scenario. Columns 1 and 3 refer to HadCM3, whereas columns 2 and 4 to ECHAM5 scenarios used as weather inputs. The best adaptation strategies among all tested ones are mapped on the bottom row.

so that well adapted cultivars might be simulated as opposed to the idealized types simulated with this exercise. Soils were assumed to be distributed on a flat terrain. This may significantly alter the soil water balance in areas with steep terrain. Also, in areas where soils are differentiated, ranging from high to low water holding capacity, simulation results will represent only a limited portion of actual results, although they capture the predominant features of the system due to climate.

Production systems were abstracted at the level of 'crop', ignoring possible typologies of cropping systems. If cropping systems were analysed instead, crop performance in a given cell would result from its performance in different rotations and under different inputs of resources. However, simulation of cropping systems, hence including a carry-over effect, would require at least the simulation of carbon and nitrogen in the soil, which at this scale is strongly data-limited.

The effects of elevated CO_2 on crop growth and yield included in the BioMA platform are consistent with current findings (Tubiello *et al* 2007).

Nonetheless, it is widely expected that CO_2 response in farmers' fields will be lower than those found experimentally even under good management practices, so the functions implemented in the simulations of this study are likely to represent an overestimate of actual field responses (this also applies to baseline yields, but possibly to a somehow lower extent if the baseline is less stressful). It must be pointed out that a positive effect of CO_2 will not be large for simulations centred around 2020 and 2030, although recent studies point to an effect of increased yield for C3 plants between 10–20% (Gornall *et al* 2010).

The key point in the time horizons studied is what choices to make with respect to the variability due to different realizations of the same emission scenario, with a focus primarily on Southern Europe. As discussed, rainfall occurrence is the main driver in the two coming decades, and the projections can be substantially different. Using the achievement of a sufficient alleviation via autonomous technical adaptation to decide if public intervention is required to ensure sustainability, would confine the source of uncertainty

to the accuracy in representing production system behaviour via cropping system models. However, the magnitude of difference of rainfall patterns across realizations of the emission scenario is substantial and can change a potential hotspot to a stable production environment and vice versa. Two approaches represent the extremes in using the weather input: (*i*) considering an ensemble simulation, or (*ii*) focusing on the most critical cases, at least to trigger attention so that they are verified on monitoring systems. The second approach would preclude long term investments due to the accepted uncertainty of environmental conditions. Provided that there is no technical reason to exclude the worst case scenarios as possible, making a choice on the approach to adopt has no technological driver, and becomes a political choice.

The impact on research and development appears to be firstly in the direction of building an infrastructure to re-run analysis once new information is made available. Analyses at the level of detail of this study and greater continue to be data-limited, suggesting an effective action to share data and increase information suitable for these studies. Improving data availability should primarily enrich the base of genetic resources which can be simulated, both as means of possible alleviation in the short term, and also to better account for the impact of agro-management choices; if a true lack of valid genetic resource would emerge, it would provide specific information for ideotyping. Also, as in Donatelli *et al* (2011), the regional level of analysis should be implemented to get closer to real production systems in the areas which are flagged as potential hotspots. The implications on data availability would be massive. Certainly, there is a need to make studies reproducible by third parties, for comparison and for further refinement of the analysis.

5. Conclusions

Primarily, the analysis on time slices of the coming 15–20 years, based on currently available climate simulations, showed that the most important factor is the spatially distributed water availability from rainfall. In such time horizons, different GCM and emission scenarios presents small differences in air temperature, but substantial differences in rainfall patterns in both Southern and Northern Europe.

The simulation including technical adaptation has shown in many cases an alleviation of impacts, especially under the HadCM3 scenario in Southern Europe in general, and with a more modest effectiveness in Southern Spain. Wheat and rapeseed showed generalized improvements in Northern Europe, whereas sunflower did not perform well under both realization of the A1B emission scenario in a large belt from central France to the most eastern area of Europe considered. It must be pointed out that such results were obtained via adjustment of technical management, without

assuming a technological advance (e.g. known varieties were simulated, without exploring possibly improved varieties). Also, more favourable patterns of rainfall may lead to increased availability of water, hence maintaining the feasibility of irrigation.

The picture presented by these simulations, certainly to be corroborated by further analysis, presented, as possible scenarios, substantially different outcomes from the generalized concept that agriculture will become unsustainable in Southern Europe. There are likely to be critical spots, but possibilities deriving from climate scenarios do not exclude opportunities in the time horizon considered. It is also worth mentioning here that in the results presented, the effect of economic feedbacks was not considered, e.g. costs of alternate technologies or levels of fertilizer application in response to changes in prices that would be triggered by the initial climate impact. It should be noted that the incorporation of such technological change and economic feedback would tend to further reduce adverse impacts of climate change.

Continuous improvements in knowledge about weather scenarios demand a simulation system to quickly update simulation results based on the input dataset that become available. At the same time, the results confirm that the temperature increase will both broaden agricultural management options and lead to potentially higher yield levels in Northern Europe. One aspect that requires specific analysis is related to extreme events which may lead to crop failure, even in the context of possibly improved weather patterns.

Acknowledgments

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