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Estimating Impact Assessment and Adaptation Strategies under Climate Change Scenarios for Crops at EU27 Scale

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Abstract: Policy makers at European and national level demand for estimates of potential vulnerability of agricultural production. Estimates are requested specific to province level, and articulated for crops. The base of such estimates is the biophysical representation of crop responses both under conditions of no adaptation, and exploring the level of adaptation which could be acted on autonomously by farmers. However, producing such estimates poses significant challenges due to the usability of climate inputs to simulation models, to reliability and completeness of data, to the level of abstraction to be chosen, and to technological aspects. This study provides an impact assessment of climate change scenarios on agriculture over EU27 focused on the time horizons of 2020 and 2030 with respect to a baseline centered on the year 2000. Potential and water-limited yields are simulated for 3 priority crops (wheat, rapeseed and sunflower) over a 25 by 25 km grid using the CropSyst model implemented within the BioMA modelling platform of the European Commission. Input weather data are generated with a stochastic weather generator parameterized over RCM-GCM downscaled simulation from the ENSEMBLES project, which have been statistically bias-corrected. Two realizations of the A1B emission scenario within ENSEMBLES are used, based on the HadCM3 and ECHAM5 GCMs, which respectively represent the “warmer” and “colder” extremes in the envelope of the ensemble with regard to the air temperature trends, and different with respect to rainfall patterns. Alleviating the consequences of unfavorable weather patterns is explored by simulating technical operations which can be acted on by farmers, highlighting the limits of autonomous adaptation, hence estimating potential vulnerability hotspots. Data are presented focusing on the difference between the baseline chosen and the 2020 and 2030 time horizons. Both data (accessible via web services) and the simulation platform are available for non-commercial use.

Keywords: climate change, adaptation, crop growth modelling, Europe, BioMA.

1. Introduction

At the global scale, climate change is assumed to be the major driver for changes in agricultural systems and crop productivity in the coming decades and has gained significant attention because it threatens global food security [Gaiser et al. 2011]. In Europe, the present climatic trend indicates that in the northern areas, climate change may primarily have positive effects through increases in productivity and in the range of species grown [Alcamo et al. 2007], while in southern areas, (i.e., the Mediterranean basin) the disadvantages may predominate with lower harvestable yields, higher yield variability and a reduction in suitable areas for traditional crops [Olesen et al. 2002]. However, even if such general trends could be confirmed, the heterogeneity of weather patterns calls for a finer verification of potential impacts and of the adequacy of adaptation measures which could be autonomously acted on by farmers. Also, there is a direct interest in evaluating potential adaptation in the short to medium term, when the assumption of known management systems to be used as starting point can be considered acceptable. This study aimed at making an estimate of potential vulnerability of water-limited yields under a future climate scenario for EU27 member states Winter wheat (*Triticum aestivum* L.), Rapeseed (*Brassica napus* L.), and Sunflower (*Helianthus annuus* L.) were considered in this study in order to analyze the specific interactions between the changing climate and crops having different seasonal growth cycles.

2. Materials and methods

2.1. Database description

Input weather data are generated with a stochastic weather generator trained over RCM-GCM downscaled simulation from the ENSEMBLES project and which have been statistically bias-corrected [Dosio and Paruolo 2011]. The time horizons that are studied are 2020 and 2030, and the comparison is done against a baseline centered on 2000, considered as representative of current conditions. The two most extreme realizations of the A1B emission scenario with respect to temperature increase from the ENSEMBLES dataset were used, thereby providing a “cold” and “warm” realization based respectively on the ECHAM5 and HadCM3 GCM models. The 6 resulting climate datasets (2 realizations x (2 horizons + 1 baseline) are all used to run crop simulations. Simulations are run on a 25 x 25 km grid that covers Europe in the Lambert Azimuthal Equal Area projection. Weather data are described by Donatelli et al. [2012]. The coverage of soil profiles is not uniform throughout Europe, and the quality of information included in our database cannot be considered as equivalent for all countries and records. Therefore a synthetic soil profile was used for all cells and for all the simulation runs, representing a loam soil with medium water-holding capacity, on a flat land. 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 two time windows 2020 and 2030 respectively.

2.2. Simulation model

CropSyst [Stockle et al. 2003] 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 and on environmental impact. In the presented work, the model was used to simulate crop development and yield under potential and water-limited conditions. The simulation of crop development is mainly based on the thermal time required to reach specific development stages. The core of the model is the estimate 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. Furthermore, the use of a modified version of the model allowed for considering the effect of increasing atmospheric carbon dioxide concentration on crop water use efficiency (WUE) and radiation use efficiency (RUE) [Tubiello et al. 2000]. The model was re-implemented in the CropML library [Confalonieri et al. 2012] and used with soil and agro-management components in a modeling solution run in the BioMA platform of the European Commission.

2.3. Model set – up

A division of the study area (EU27 member states) into zones was applied prior of making crop parameters calibration. The actual model runs were, however, done on climatic grid cells, which are the basic spatial units for weather data. One zone consequently contains a number of climatic grid cells. The whole study area was divided into three latitudinal zones, each having a unique crop variety assigned to it in terms of duration of the biological cycle (temperature sum requirements), with fixed sowing dates. The CGMS (Crop Growth Monitoring System, JRC-MARS) crop calendar was used to set sowing dates of current agro-management practices in the simulations. Model calibration requires the adjustment of parameter within a reasonable range of fluctuation suggested by research experiments, expert opinions, or background knowledge. Following this principle, a few crop input parameters were calibrated and adjusted based on outputs of growth characteristics and minimizing the differences between actual (as reported in literature for crops growing in well managed conditions) and simulated yields. Statistics cannot be used in this process given that the base of calibration is potential growth, and statistics contain yield levels showing a variable yield gap due to management and environmental conditions. Statistics can be used to evaluate model performance in conditions in which limiting factors of actual yields are accounted for in simulation (e.g. water availability, assuming that nitrogen and biotic and abiotic stresses do not occur). Other crop specific input parameters required to feed the model were extracted from the literature (refer Table 1). We explored the advantages of specific adaptation strategies for the target crops under realization of A1B scenario. Sowing dates of selected crops were shifted by either bringing forward or delaying sowing within the interval (S_{0-10}, S_{0-20}, S_{0+10}, S_{0+20}, days) with respect to baseline, S_0 being the standard (baseline conditions) sowing date. Growth performance of hypothetical varieties under conditions of climate change was also tested by using crop parameters of either earlier or longer maturity genotypes. Finally, the results presented here refer to crops which were simulated under rain-fed conditions.

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; SE= Southern Europe; CE= Central Europe.

Parameter	Wheat			Rapeseed			Sunflower				
	Value			Value			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	1700	900	1000	1000	1150	1150	1150	°C- days	C
Degree days physiological maturity	1600	2300	2500	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)	25	30	20	30	25	25	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
Stem/Leaf partitioning coefficient (p)	1.5	2	1.5	3.5	3.5	4	4	4	4	m^2 kg^{-1}	C
Leaf duration	1200	1600	1700	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	4	3.5	2.5	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	6	6	6	8.4	8.4	8.4	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

L = Donatelli et al.(1997); Bechini et al. (2006); Torriani et al. 2007); Todorovic et al.(2009)

3. Results and Discussion

This study has generated a substantial amount of results given the combination of crops, time horizons, yield levels and adaptation strategies. Since these cannot all be described in detail in this paper, the following discussion and maps are focused on water-limited wheat for both time horizons. A briefer discussion is presented afterward for rapeseed and sunflower. A web portal contains the detailed results and methodologies (http://agri4cast.jrc.ec.europa.eu/peseta)

3.1. Wheat

The overall expected situation of wheat is very different whether the “warm” or the “cold” realization of the A1B scenario is used. Figure 1 resumes the expected situation of water-limited wheat yields in 2020 according to which model is used. The differences is spatial patterns of yield reflect the substantial differences in rainfall patterns between ECHAM5 and HadCM3 rainfall [Donatelli et al. 2012].

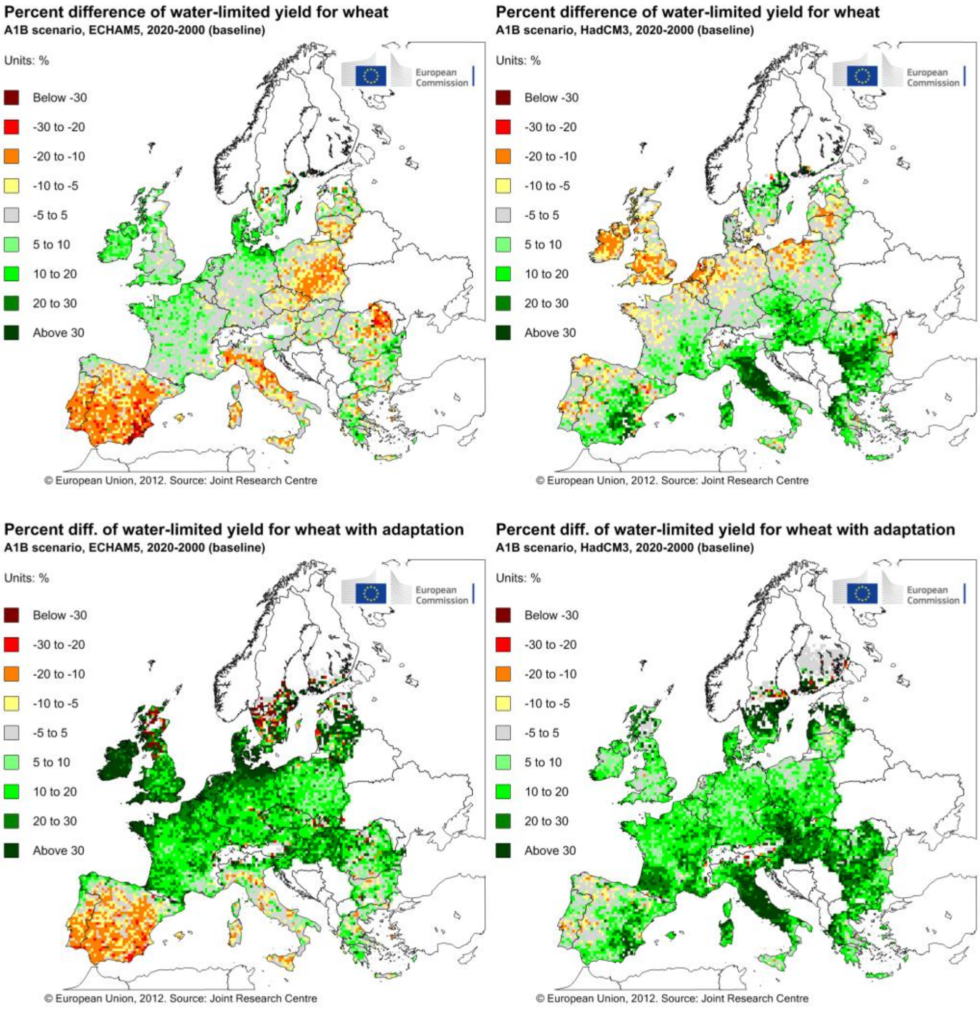


Figure 1. Percentage change in simulated water-limited yield for winter wheat in 2020 with respect to the 2000 baseline under the A1B scenario as modelled using ECHAM5 (left column) and HadCM3 (right). Upper maps to do not take adaptation into account whereas the bottom maps show the result for the best adaptation strategy for cell.

The reason for increase in yields in Southern Europe when rainfall is available (that is, with the “warm” HadCM3 realization) is the shortening of the crop cycle that may impact positively by improving the avoidance to summer water stress. The positive effect of avoidance of summer stress was observed already via simulation with different GCM inputs at a location of Southern Italy [Donatelli et al. 1998; Harrison and Butterfield 1996]. 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 the ones of the first studies of simulations of crop growth in future scenarios of the ‘90s. The results of the adaptation strategies (Figure 1, bottom row) show a general improvement over all of 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 wheat planting date by 10 days, and using a variety having longer growth cycle (the result do not account for a possible greater pressure of plant diseases, for instance as due to wheat rusts). Figure 2 provides the simulated yield changes for the 2030 horizon. Overall the same general conclusions can be drawn, only that due to a generalized increase in temperature, the yield increases with adaptation are slightly milder than with respect to 2020

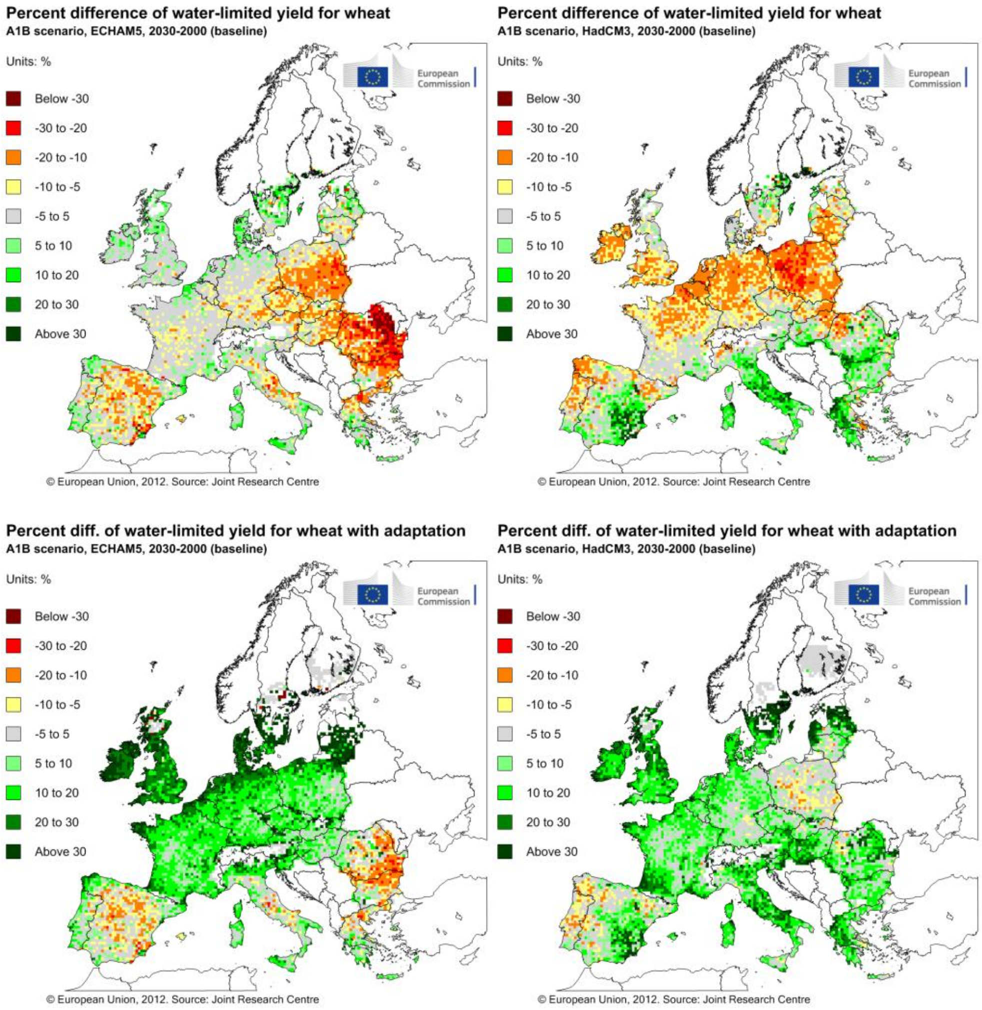
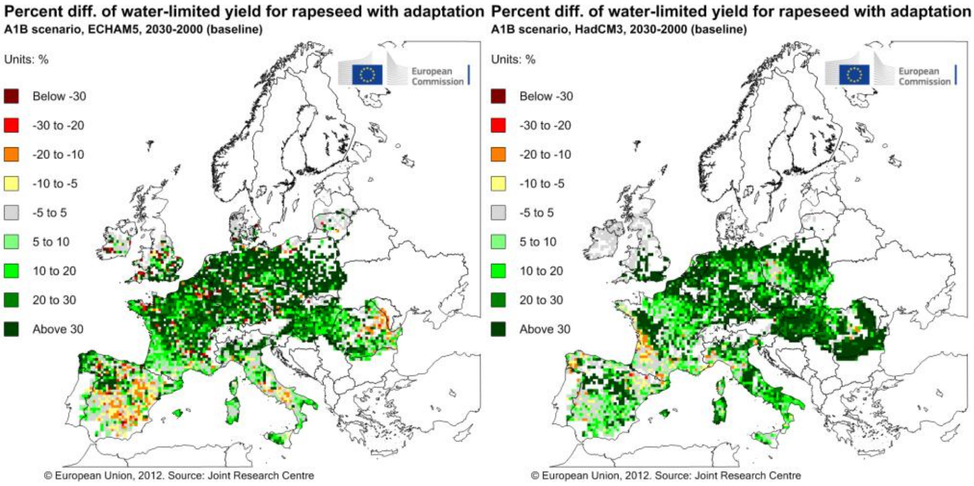


Figure 2. Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline under the A1B scenario as modelled using ECHAM5 (left column) and HadCM3 (right). Upper maps to do not take adaptation into account whereas the bottom maps show the result for the best adaptation strategy for cell.

An important point is that according to simulations under the “warm” scenario, which estimate and increase of rainfall, yield are expected to increase in Southern Europe even without adaptation because of rainfall patterns and CO_2 fertilization.

3.2. Rapeseed

There is an indication from the simulation results that by 2020 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 got even worsen in 2030 time horizon. Whereas, by 2020 yield improvements in parts of the Spain, Italy, Southern France, Hungary and Romania suggests firstly, that water is not a limiting factor because of higher amount of precipitation estimated and secondly, the positive implication of CO_2 fertilization. Adaptation resulted very effective for rapeseed as shown in Fig. 3 for the 2030 time horizon and both A1B realizations.


Percent diff. of water-limited yield for rapeseed with adaptation
A1B scenario, ECHAM5, 2030-2000 (baseline)

Percent diff. of water-limited yield for rapeseed with adaptation
A1B scenario, HadCM3, 2030-2000 (baseline)

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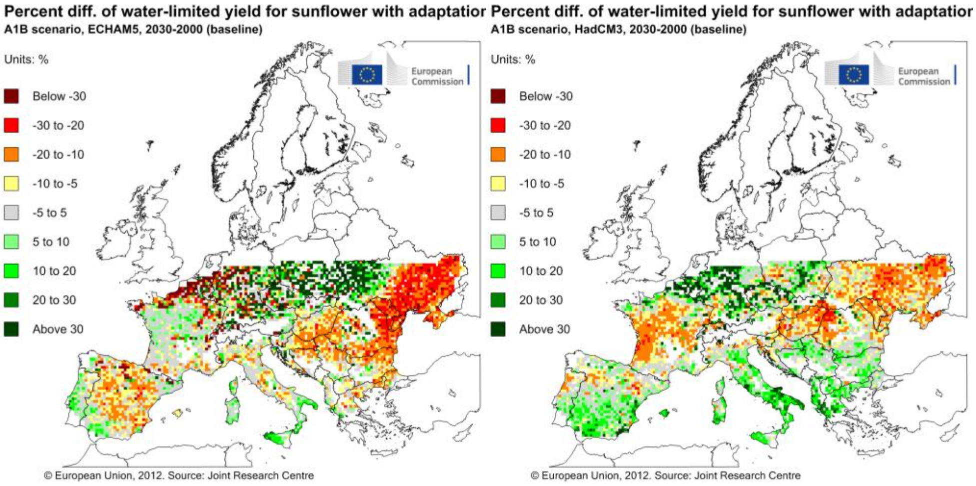
Figure 3. Percentage change in simulated water-limited yield for rapeseed in 2030 with respect to the 2000 baseline under the A1B scenario as modelled using ECHAM5 (left column) and HadCM3 (right). Maps show the result for the best adaptation strategy for cell.

3.3 Sunflower

The results show 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.


Percent diff. of water-limited yield for sunflower with adaptatior
A1B scenario, ECHAM5, 2030-2000 (baseline)

Percent diff. of water-limited yield for sunflower with adaptatior
A1B scenario, HadCM3, 2030-2000 (baseline)

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Figure 4. Percentage change in simulated water-limited yield for rain-fed sunflower in 2030 with respect to the 2000 baseline under the A1B scenario as modelled using ECHAM5 (left column) and HadCM3 (right). Maps show the result for the best adaptation strategy for cell.

The improvements can be directly linked to the higher precipitation compared to baseline. By 2030 the improvements get milder in South European countries and countries in Eastern Europe see 10-30% yield decline. The assertion can be summarized by higher evapotranspiration coupled with less rainfall compared to baseline period.

3.4. General remarks

Exploiting management options to avoid or reduce negative effects of climate change is an imperative step in climate-sensitive activities. Firstly, due to space constraint the data presented are differences in percentage, hence have a different meaning in terms of absolute quantities according to the baseline production level. The current study has considered crops abstracting from production systems and specific soils. Also, it has necessarily used simplified agro-management settings. This leads to results which must be considered as first estimates of potential vulnerability, to be further evaluated under more detailed, context-specific, simulation conditions in a two steps analysis as proposed in the AVEMAC project [European Commission, 2012]. Furthermore, other aspects which were considered in the simulations, such as the impact of disease and abiotic stresses, are not presented here.

The simulations presented in this paper indicate that adjustments in sowing dates and use of diversified maturity cultivars could not only alleviate the impact of new climate scenarios, but could even lead to potential gains of crop yield in some EU27 areas. Delaying sowing dates for fall-sown crops mostly accounts for the increased temperature regimes. Using longer maturity crop varieties for spring sowing crops benefits of longer growing seasons, when avoidance to summer stress is not a factor. Simply shifting sowing dates allows grown crops to develop under more favorable either thermal or hydrological (or both) conditions. However, this adaptive strategy in case of wheat does not work well at some of the locations (for instance in parts of Poland, Portugal and Spain). This is because at these locations, under the climate change scenarios considered, low rainfall coupled with increased temperature span across the whole year, leaving no favorable growth conditions. In these areas either different crops or use of substantially different management strategies (e.g. moving from rain-fed crops to irrigated crops) appear needed to sustain agricultural production.

However, the most important point appears to be the variability of projected rainfall patterns, which led to partially contrasting results, and consequently to possibly different adaptation strategies. Choosing to refer either to the worst case scenario or to an average of both, which would statistically indicate a limited future impact on the crops evaluated with respect to water and temperature regimes, cannot be based on technical evidence. Moreover, even if there is a strong response to precipitations, the effectiveness of adaptation measures is diversified considering the interaction species x environment, indicating the need for a detailed context specific analysis.

4. Conclusions

We investigated the adaptation options which could offset climate change impacts on EU27 member states agriculture. The results presented in this paper refer to abstraction of crop growth with respect to production system, and considering growth as limited by weather variables and soil water; pests, diseases, and nutrients limitation is not accounted for in simulations. The results show that sowing dates and use of different varieties, the latter in terms of duration of the crop cycle, may be effective in mitigating the adverse effects of climate change. Sizable differences between adapted and current crop cultivars indicate that promoting cultivars with either shorter or longer maturity, combined to adjustments to planting dates, could potentially help in alleviating potentially detrimental effects. At the same time, the results show the variability of responses according to spatial location and to the different possible realizations of emission scenarios, thus calling for rigorous research and investment in enhanced modelling infrastructure and data. Addressing the impact of climate change on agricultural production using state of the art tools and methodology, via context specific, transparent analysis is the only way to support policy makers beyond the often excessive simplifications presented as estimates of agricultural production under climate change.

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Acronyms

BioMA=Biophysical Models Applications; EU27=Current Member States of the European Union; GCM=Global Circulation (Climate) Models; RCM=Regional Climate Models;

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