Assessing Agriculture Vulnerabilities for the design of Effective Measures for Adaption to Climate Change

(AVEMAC Project)

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Executive summary

This report presents the final results of the study named AVEMAC (Assessing Agriculture Vulnerabilities for the design of Effective Measures for Adaptation to Climate Change). This study has been realized in collaboration of the Actions AGRI4CAST, GeoCAP, AGRI-ENV, and AGRITRADE of the Institute for Environment and Sustainability (IES) and the Institute for Prospective Technological Studies (IPTS) within the European Commission's Joint Research Centre.

The motivation of this study has been the lack of information on vulnerabilities, risks, and needs for the adaptation of European agriculture under a changing climate in the next decades. Directorate-General for Agriculture and Rural Development (DG AGRI) therefore asked the scientific support of the Joint Research Centre to conduct this study in order to present the existing knowledge through mapping and characterizing the vulnerabilities of EU agricultural systems to climate change, to come up with a methodological framework and to propose follow-up actions. Eventually the results of this study shall help the formulation of appropriate policy options and the development of adequate policy instruments to support the adaptation to climate change of the EU agricultural sector.

An impact assessment of climate change scenarios on agriculture was run covering EU27, being centred on time horizons centred on the years 2020 and 2030, in comparison to the baseline centred on the year 2000. Two realizations of the Intergovernmental Panel on Climate Change (IPCC) were used as the input of the analysis, based upon emission scenario A1B (i.e. scenario of a more integrated world with a balanced emphasis on all energy sources) from the runs of the global circulation models HadCM3 and ECHAM5, both bias-corrected and downscaled from the original ENSEMBLES data set by the same regional climate model to a 25 km grid resolution. The two chosen realizations represent a "warm" and a "cold" realization within the A1B scenario with regard to the air temperature development, averaged over Europe and the envisaged time horizons. The analysis was run on priority crops, identified as maize, wheat, rapeseed, sunflower, and rice. An exploratory analysis on grapevine phenology was also run for the horizons 2020 and 2050.

Two types of analysis were performed as the basis of the assessment. The first one focused on specific crop responses as derived from crop growth simulations forced with climate data of the two realizations of the A1B emission scenario. The simulations for both realizations were performed for the time horizons 2020 and 2030 in comparison to the baseline of 2000, and included the abstractions of the production systems potential production, water-limited production, and production limited by diseases. The second one computed static indicators as proxies of potential vulnerabilities of agricultural systems, expressed as changes in the classification of agricultural areas under climate constraints in Europe. Four agro-climatic indicators of potential vulnerability of agricultural areas were computed – length of growing period, thermal-time sum, heat stress and aridity index – and aggregated at NUTS2 level. The analysis was run for both the "warm" (HadCM3) and "cold" (ECHAM5) realization of the emission scenario A1B. The results present changes in the areas under climate constraints for 2020 and 2030 as compared to baseline.

Assessing the importance of climate change vulnerability requires not only the localisation of relative yield changes, but also the analysis of the impact of the change on the acreage affected. Consequently, the simulation results of the impact assessment on crops were further processed to estimate the potential changes in production at NUTS2 level. This was achieved by relating the simulation results to farm typologies from the ASEMARS and SEAMLESS projects and then comparing the aggregated simulation results to reference statistics of the year 2005.

In this study adaptation measures have not been considered in the model simulations. Results refer to the simulation of abstractions of current agricultural systems under scenarios of climate change.

The impact assessment of climate change on crops at 25 km grid scale has shown contrasting results in response to the different realizations of the emission scenarios. One key aspect has been the changing rainfall pattern in Southern Europe, which can lead to either an improvement or a deterioration of the performance of crops, especially for winter sown crops, but also for sunflower that uses the first part of the year to complete its cycle.

Under potential production the simulations for wheat showed a negative response at northern latitudes, and a mainly unchanged yield response at southern latitudes. For rapeseed a negative potential impact was simulated at southern latitudes. Sunflower yield was simulated to potentially improve at northern latitudes, but with negative effects on yield at southern latitudes. The simulation results for maize were potentially positively at northern latitudes, but negative at southern latitudes. The potential production level simulated for rice was positive. Finally, simulations for grapevine phenology showed predominantly an advance in the development stages, indicating a large potential vulnerability of *terroir*-bound production.

Under water-limited production the different precipitation patterns estimated by the two GCMs led to a different response of rain-fed crops (wheat, rapeseed, sunflower). With the "warm" realization of the HadCM3-derived weather data, potential yields were simulated to improve in Southern Europe. Simulations forced with ECHAM5-derived weather data showed a smaller impact on yields of the rain-fed crops in Southern Europe.

The analysis of vulnerability, which integrates results from both the bio-physical simulations and the agro-climatic indicators, provides an indication of which regions may expect potentially significant production changes by the time horizons of 2020 and 2030. In the warm scenario little to no potential changes are expected for grain maize, sunflower and rapeseed by 2020; however, by 2030 the analysis indicates potential decreases in production in various areas, if adaptation to climate change is not taken into account. The cold scenario foresees a potential increase of grain maize production in several southern regions by 2020, which is confirmed in the simulations for 2030. For the warm scenario wheat production is estimated to increase potentially in some regions of Southern Europe by 2020, but these potential increases are not expected to be maintained by 2030; furthermore, Northern Europe is estimated to experience reductions in wheat production by 2030. The cold scenario does not foresee significant potential increase for wheat and the regions affected by a significant potential decrease are mainly different from the ones that are indicated with a potential decrease by the warm scenario. An indication of the farm types that could be more vulnerable than others is further obtained crossing this analysis with a dominant farm typology layer.

It must be pointed out that simulation results of a climate scenario with a positive impact on crop performance could be considered a realistic realization of a possible future, i.e. this outcome might become reality. On the other hand, simulation results with negative impacts on crop performance do represent a pessimistic outcome, because no adaptation measures have been included in this analysis that in reality would be effective and could limit the realization of the simulated outcome. Therefore the outcome of simulations with negative impacts can be considered as potential vulnerabilities only that do not allow deriving any conclusions on the actual vulnerabilities. Having potential vulnerabilities turning into actual vulnerabilities can be overcome, if corrective means are technically available at that time and if they are affordable by farmers.

The analyses of this study must be considered as a first step only, since they have neither included adaptation nor a bio-economic evaluation of estimated vulnerabilities. Therefore main aspects of and requirements for a possible future integrated analysis at EU27 level to address climate change and agriculture with the target of providing policy support, including relevant workflows, are presented.

This report will be made available on DG AGRI studies web page which can be found at http://ec.europa.eu/agriculture/analysis/index_en.htm, DG AGRI climate change web page at http://ec.europa.eu/agriculture/climate-change/index_en.htm and the Joint Research Centre MARS web pages at http://mars.jrc.ec.europa.eu/mars/Projects/AVEMAC. There will be also available a link to this study in the web portal of the European Climate Adaptation Platform (CLIMATE-ADAPT) http://climate-adapt.eea.europa.eu/.

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Introduction

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The objectives of the study, in the order of the chapters of this report, are:

1. To provide a literature overview of existing work in this field, and establish baseline choices for scenarios, GCMs, and models for the study;
2. To refine and enhance the existing EU level infrastructure (provided by the JRC) to generate weather data of selected climate scenarios for the 2020 and 2030 horizon as input to bio-physical modelling and agro-climatic analysis;
3. To design an appropriate methodological approach for the characterisation and initial mapping of the vulnerabilities of EU agricultural systems to climate change. This non-crop specific analysis will be based on agro-climatic indicators for the identification of agricultural areas under climate constraints, and evaluate the impact of a changing climate on the delineation of areas under climate constraints;
4. To generate bio-physical model estimates for a shortlist of priority crops, spatially mapped as far as NUTS2 level, of crop yield under future climate change scenarios, taking into account a specific range of integrated considerations necessary for adaptation strategy assessments;
5. To characterise, spatially, the vulnerability of EU regions. Using the above mentioned typology, the resource inputs affected by climate change (in particular water availability), production and output characteristics will be identified in a spatially explicit manner, and be used to provide an up-to-date and in-depth analysis of the most significant vulnerabilities of different European agricultural systems in the main production regions, for 2020 and 2030;
6. To establish a methodological framework for the assessment of the possible impacts and adaptation potential, in order to assist the assessment of adaptation measures, and to make proposals for follow up actions in support of decisions for selecting policy measures for adaptation, on the basis of environmental and econometric reasoning.

These objectives correspond to the six main chapters of the report. The authors that have contributed to each work-packages are mentioned at the beginning of each chapter, along with their affiliations.

Finally, the report presents conclusions and recommendations, together with references and a glossary, at the end of this document.

1. Literature overview

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1.1. Introduction

"*The warming of the climate system is unequivocal*". This statement comes from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007a), which further states that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentration. According to Rosenzweig et al. (2008), this anthropogenic climate change is having a significant impact on physical and biological systems at both the global and continental scale (although for some continents, there is not enough long-term observation data to provide a reliable conclusion).

There is a wide range of processes through which climate change could potentially impact global-scale agriculture in the early twenty-first century. Due to the complexity governing the interactions between these processes and the uncertainty associated with modelling them, it is not presently possible to reliably quantify the aggregate impacts of climate change on global-scale agricultural productivity (Gornall et al., 2010). 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 so much, but this will be outbalanced by increased 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 can be generalised 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, Petersen, et al. 2002; Maracchi, Sirotenko, et al. 2005; Falloon & R. 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 (Schär 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. In order to implement appropriate policies, the EU requires adapted tools to characterise spatially the vulnerability of its agriculture based on future climate predictions. The present document aims at providing a broad overview of the methodological approaches that are necessary to achieve this goal along with a review of existing work in this field. The basis on how future climate can be estimated is first outlined. The problems of rendering these estimations usable for impact studies are then discussed, after which actual methods for assessing climate change impacts on agriculture are presented. A brief description of projects realized in Europe is presented before resuming the choices that can be taken for the present project based on this literature review.

1.2.Modelling future climate

The basis for assessing potential impacts of climate change is future climate predictions. To obtain such predictions, it is necessary to have a reliable model of the climatic system and to use it to estimate possible future outcomes. A clear distinction has to be done between these two concepts: models, which are based on physical laws, and scenarios, which are a coherent, internally consistent and plausible description of a possible future state of the world.

Global and regional circulation models

Currently, the most advanced tools used for simulating the chaotic nature of the climate system are coupled Atmosphere-Ocean General Circulation Models (AOGCMs or GCMs for short). GCMs model the physical processes and dynamic interactions of the global climate system in response to sea and land surface boundary forcing. The calculations are discretized at the levels of cells on a 3-D grid, whose size depends on the available computing power and on the implementation of the model.

Several GCMs have been created and are maintained by different institutions across the globe. Some of the commonly used GCMs in the scientific literature are the HadCM3 model (Collins et al., 2001) developed at the Hadley Centre in the United Kingdom, the ECHAM5 model (Roeckner et al., 2003) developed at the Max Planck Institute for Meteorology and the GFDL CM2 (Delworth et al., 2006) developed at the NOAA Geophysical Fluid Dynamics Laboratory in the United States. All three have been leading climate models used in the recent IPCC assessments.

Various GCMs exist and provide different simulations of present climate. The reasons for these variations include that, although the atmospheric components of most global climate models are similar (actually similar to a weather forecasting model), the representations of the ocean, sea ice and land components vary from model to model, with some including more simplified representations than others (Parker, 2010). Furthermore, since the actual equations representing the various physical processes cannot generally be solved analytically and the computer power necessary for numerical solutions is excessive, different models may have different simplifications to these equations that may translate into different simulations.

While the spatial resolution of GCMs is sufficient to simulate the averaged *global* climate, their output is often unsuitable when the scale of interest is refined. At a finer scale or higher resolution, several factors complicate climate modelling, including local topography, land cover and land use features, the presence of atmospheric aerosols and other pollutants.

To address climate modelling at regional scale, Regional Climate models (RCMs) have been developed. These are typically driven by initial and boundary conditions supplied by a GCM (Giorgi and Mearns, 1991; Murphy, 1999; Mearns et al., 2001). Within the framework of a project called PRUDENCE[1], Jacob et al. (2007) assessed the performance of an ensemble of coupled GCMs-RCMs over Europe by comparing their simulations with the 1961-1990 observed climate archive. They report a general warm bias during summer and winter while the transition periods are characterized by a tendency towards a cold bias. Modelled temperature variability is larger than that of observations, but this is less marked for precipitations. RCMs generally reproduce well the patterns of their respective GCMs, but the authors warn that in some cases there are differences in regional biases.

Climate change scenarios

In order to predict the future evolution of the climate system given anthropogenic "forcing" (such as increases in greenhouse gases, GHGs) it may be subject to, it is necessary to run the models under a given emission *scenario*. A scenario is a coherent, internally consistent and plausible description of

[1] Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects

a possible future state of the world. It is important to recall that scenarios are not predictions or forecasts (which indicate outcomes considered most likely), but are in fact alternative images without ascribed likelihoods of how the future might unfold.

The IPCC proposed a Special Report on Emission Scenarios (SRES) in which scenarios are classified along two axes whether the future is either more globalised or regionalised, and whether it will be more environmentally or economically centred (Nakićenović et al., 2000).

The nomenclature proposed in SRES to label these emission scenarios is as follows: letters A and B indicate that the focus is respectively economic or environmental and numbers 1 and 2 describe whether the world will be homogeneous (i.e. globalised) or heterogeneous (i.e. regionalised). Sub-categories are used for the globalised, economically-oriented scenario A1 which is further divided with respect to the technological emphasis placed energy: A1FI (for a fossil-fuel intensive scenario), A1B (for a balanced emphasis on all energy sources) and A1T (emphasis on non-fossil fuel energy sources).

The Working Group 1 report of the IPCC 4th Assessment Report (IPCC, 2007b) provided a comprehensive review of the understanding of potential climate change under this range of future scenarios based on state-of-the-art complex climate models. The scenarios A1B, A2, B1 and B2 are considered to represent the broad range of possible outcomes with A2 and B2 being the top and bottom boundaries.

SRES has been the subject of much discussion. The scenarios within SRES only explore emission pathways in the absence of climate policy. Johns et al. (2011) have therefore also explored the consequences of an aggressive mitigation scenario (E1), constructed using an integrated assessment with reduced fossil fuel use for energy production aimed at stabilizing global warming below 2 ºC compared to pre-industrial level. Anderson & Bows (2011) argue that staying below 2 ºC is very unlikely, notwithstanding high-level statements to the contrary in the political sphere. They suggest that a radically different framing of the mitigation and adaptation challenge than what is suggested in many analyses is necessary, and further argue that 2 ºC should be the frontier between 'dangerous' and 'very dangerous' climate change instead of the boundary between 'acceptable' and 'dangerous' climate change as it is currently understood by the global community.

There has also been discussion on whether a strategy aimed at maintaining GHGs concentration (and thus temperature) under a certain threshold (i.e. stabilisation profiles), versus allowing a peak to occur after which the level would go back down. On the basis of cost-effectiveness considerations, peaking profiles may be preferable to stabilization profiles in order to reach long-term temperature targets (den Elzen and van Vuuren, 2007).

The SRES storylines and their generalised quantitative indicators are defined at a global scale. For a finer analysis at global scale and for regional-scale impact assessments, Arnell et al. (2004) recommend:

(i) better disaggregation of the storylines to a finer spatial resolution which is more representative of the regional context;

(ii) an explicit incorporation of uncertainty in population, GDP and land cover for each emission scenario;

(iii) to use a wider range of socio-economic scenarios.

Along these lines, the four main SRES scenarios (A1B, A2, B1 and B2) have been extended by Abildtrup et al. (2006) to include much more agricultural details in socio-economic terms. Some studies had done a previous work over Europe oriented towards land use change (Rounsevell et al., 2006) and used them to project changes in crop productivity (Ewert et al., 2005) and in the spatial extents of European croplands and grasslands (Rounsevell et al., 2005).

Uncertainty in climate projections

Climate change projections realized by running GCMs (or RCMs) under different emission scenarios are intrinsically subject to a significant amount of uncertainty. To illustrate this point, Paeth et al. (2008) investigated to what extent various state-of-the-art climate models agree in predicting changes in the main features of El Niño-Southern Oscillation (ENSO) and the monsoon climates in South Asia and West Africa. The study found that the detected response barely exceeds the level of natural variability and the systematic inter-model variations are larger than the impact of different IPCC scenarios.

Parker (2010) described the uncertainty in climate change projection as follows. Uncertainty can originate from the choice in initial conditions of the modelling system, but also from the choice of the modelling equations. For the latter, several reasons contribute to the uncertainty: the fact that some physical processes are still not entirely understood; the oversimplification required in the equations (even for fully understood phenomena) due to computational limitations for numerical solutions (since in many cases these are analytically unsolvable); and due to the fact that some important processes occur at scales which are finer than those of the climate model (and must therefore be somehow represented at the coarser scale).

Three major types of uncertainty that can be recognized in global climate simulation today:

(i) initial condition uncertainty;

(ii) structural uncertainty which relates to the form modelling equations should take;

(iii) parametric uncertainty which depends on the values assigned to different parameters within the equations.

The uncertainty regarding climate change predictions has led to using ensembles of simulations in order to have a picture of the potential range of outcomes (Collins, 2007). These ensembles can be constructed by either using a single model with different initial conditions, by using a set of different models with equivalent settings or by using a combination of both. Ensembles can further be created using perturbed-physics in which a range of values for parameters of a single climate model are set according to prior distributions. Such method however can lead to a very large amount of simulations due to the very high number of uncertain parameter in GCMs.

Several European projects were designed with this ensemble approach. The PRUDENCE project had the objective to establish a large ensemble of regional climate change simulations for Europe for the time frame from 2070 to 2100 (Christensen and Christensen, 2007). PRUDENCE was followed by the ENSEMBLES project whose main objective was to allow uncertainty in climate change models to be measured by producing probabilistic projections of European climate.

1.3. Making climate modelling compatible with impact studies

Translating climate forecasts into agricultural terms remains a challenge, due to the significant differences in spatial and temporal scales between GCMs and crop growth models (Hansen et al., 2006).

Despite an increasing ability of GCMs to successfully model present-day climate and provide realistic quantitative predictions of climate change at continental scale (IPCC, 2007b), they still have serious difficulties in reproducing accurate daily estimates at local scale. Even though GCMs operate at sub-daily scale, the spatial averaging at the coarse grid-scale distorts the temporal variability of daily weather sequences (Osborn and Hulme, 1997). This is especially true for precipitation. For instance, while a GCM may estimate monthly precipitation correctly, the daily precipitation may be spread throughout the month in a very unrealistic way (raining a little every day for example). Such distortions of daily weather variability can seriously bias crop model simulations (Semenov and Porter, 1995; Mearns et al., 1996; Hansen and Jones, 2000; Baron et al., 2005; van Bussel et al., 2011).

Statistical downscaling

A first direct way to downscale information can be realised using an entirely statistical approach (Hewitson BC and Crane RG, 1996; Wilby et al., 1998; Murphy, 1999). This entirely empirical approach relies on finding a transfer function between fine and coarse scale data based on observational data, and hoping that the same relationship applies in future scenarios. An advantage of such method is that it does not require much computing power or heavy parametrization. Ancillary data such as topography can sometimes be used in a Bayesian framework to statistically downscale temperature (e.g. Fasbender and Ouarda (2010)).

Synthetic weather generation

Downscaling CGM information can also be done using stochastic weather generators (Wilks, 1992; Semenov and Barrow, 1997). As implied by their name, weather generators will produce artificial time series of weather data. This is done based on a calibration of site-specific parameters with observed weather data at that site. The simulated weather time-series have the same statistical properties as the observed calibration data. In climate change projection studies, the calibrated parameters of the weather generator are changed with respect to the general projected change from GCMs running over a given SRES scenario. A disadvantage of downscaling using a weather generator is that spatial consistency of generated weather is often not preserved.

Dynamic downscaling using regional climate models

Perhaps the most physically sound way to downscale information is the coupling of RCMs with GCMs (Giorgi and Mearns, 1991; Murphy, 1999). There has recently been an increased effort in doing so to obtain spatial resolutions of the order of 50 km or less (Christensen and Christensen, 2007), which has led to improved quality in projections of regional climate changes in Europe. However, uncertainties remain (Olesen et al., 2007). While the spatial resolution of the simulations is improved when coupling GCMs and RCMs, the temporal distortion of precipitations and (to a lesser extent) temperature are still present. Methods have therefore been developed to correct this bias either using a simple shift (Ines & Hansen 2006) or using more complex statistical procedures based on histogram equalization functions (Piani et al., 2010). Recently, (Dosio and Paruolo, 2011) have implemented the corrections proposed by Piani et al. (2010) to mean, minimum and maximum daily temperatures and daily precipitations simulated in the ENSEMBLES datasets of RCM-GCM simulations.

1.4.Methods for assessing climate change impacts on agriculture

Various studies have addressed part of the problem of estimating the impacts of climate change on agriculture. For a recent overview of these impacts on European agriculture, the reader is directed toward Falloon and Betts (2010) and the references therein. In general, impact studies are made using two different approaches: the analysis of agro-meterological indicators or simulations of biophysical models (and more precisely crop growth models). The two approaches differ in their specific targets, strengths, assumptions and limitations.

Agro-meterological Indicators

The first and relatively simple approach to assess the impact of climate change on agriculture is to calculate agro-meterological or agro-climatic indicators. Examples of such indicators include the length of growing period, temperature conditions (such as frost or heat constraints) moisture conditions, or soil drainage conditions.

Agro-meteorological indicators of that sort have been proposed as criterions to define intermediate Less Favoured Areas (LFAs) in the European Union (Eliasson et al., 2010). The impact of climate change on agriculture can therefore be assessed based on how LFAs may appear or disappear according to climate change predictions from GCM-RCMs simulations based on SRES.

For the sake of simplification, indicators relating to the optimal temperature for crops need to be generalized. Length of Growing period is therefore defined based on the growing degree days calculated based on the assumption that there is negligible growth below 5 °C or above 35-40 °C for most crops (Porter and Semenov, 2005).

Such generalization at the European scale does not take into account that (i) crops and crop varieties have different responses to temperature and that (ii) farmers generally choose the crop variety best suited for the local conditions.

Gao and Giorgi (2008) analysed aridity indicators on the Mediterranean region calculated based on climate change projections (Gao et al., 2006) using a 20 × 20 km spatial resolution RCM driven by HADCM3 to conclude that a serious increase in water stress on agriculture is foreseen. Differences between the two scenarios analysed (A2 and B2), which represent the top and bottom end of the IPCC scenarios in terms of projected GHG concentration by the end of the 21st century, indicate the potential effectiveness of mitigation in these regions which are highly vulnerable.

Trnka et al. (2011) have recently analysed future agro-climatic conditions in Europe using such approach. Agricultural factors investigated include: potential biomass, time period suitable for crop growth, low temperature limitations, water deficiency, harvesting and sowing conditions. Indicators used in this study include (amongst others) sum of effective global radiation, number of days with water deficits in a given season, proportion of suitable days for sowing/harvesting in a given period, etc. A positive aspect of this study is the fact that impacts are reasoned according to environmental zones (based on a stratification of Europe made by Metzger et al. (2005) and Jongman et al. (2006)) instead of arbitrary administrative regions which are not necessarily relevant in agronomic, climatic or environmental terms. Also of great interest is that they focus on daily data and on variability, especially of extreme events. On the other hand, the study only uses a limited number of stations (84) to draw conclusions for the entire continent. Calculating the indicators on a grid-level could provide a much finer representation of the regional variations that are expected. Furthermore, the study is based on a "pattern-scaled" technique with weather generators, and it is expected that more accurate estimations can be obtained using state-of-the-art techniques (i.e. biased-corrected coupled GCM-RCMs).

Composite indicators, i.e. a combination of individual indicators, can be of high value for policy makers since composite indicators can potentially resume different climatic information into a single number. The downside is that they might be too complex or not transparent enough, leading to a higher probability of misinterpretation. Few studies proposing composite indicators exist, not for agro-meteorological indicators nor for impact studies, but rather for climate change (i.e. based on precipitation and temperature changes only). An example includes the Regional Climatic Change Index (RCCI) proposed by Giorgi (2006) which has latter been linked worldwide to socio-economic indicators of poverty, wealth and population (Diffenbaugh et al., 2007). Baettig et al. (2007) have proposed a composite Climate Change Index, based on individual indices in temperature and precipitation, as a measure for how strongly future climate will change relative to today's natural variability (the CCI mostly differs from the RCCI on this last point: setting today's natural variability as a benchmark).

While assessments based on indicators can be implemented in a relatively simple way and can be robust or more sensitive to specific climatic events, they must still be regarded as what they are: indicators. They offer a more qualitative overview of the impact rather than a quantitative one.

Biophysical modelling for impact studies

The only suitable tools for quantitative assessment of future environmental conditions on biomass production are biophysical models, out of which crop growth models are those which can be used for estimation global crop productivity.

There are many reports of agricultural climate change impact assessments based on simulation modelling. A not-so-recent review (Tubiello and Ewert, 2002) mentioned more than 100 such assessments made worldwide at different scales and using various different simulation models. A much more recent review (Jaggard et al., 2010), however, mentions only three large studies which have estimated the impact of future climate on global yield using crop growth models fed by GCMs: Parry et al. (2005), Fischer et al. (2005) and Nelson et al. (2009).

However, the consequences of the global scope of these studies are: (i) the use of relatively simple crop simulation models with (ii) general parametrization which are probably not realistic in many conditions and (iii) a lack of detail concerning impacts over Europe since Europe only covers a small fraction of the globe.

Rather than using crop growth models, it is more appropriate to tackle the issue by modelling cropping systems. Indeed, farmers are able to respond to changing environmental conditions by modifying the management practices, such as by choosing more favourable cultivars, changing sowing or harvesting dates and even by changing rotation patterns. These responses ought to be taken into consideration when studying adaptation to climate changes since these may determine whether crop yields can be maintaining or even increased in the future.

An example of cropping system model is CropSyst (Stockle et al., 1994) which has already been used to study climate change and CO_2 increases in different locations (Tubiello et al., 2000). CropSyst has also been used to evaluate the impact of climate extremes on crop yields in the Mediterranean region (Moriondo et al., 2011).

Some impact studies attempt to go beyond just yield potential estimation by adding an extra layer of socio-economic modelling. For example, Audsley et al. (2006) analyse agricultural land use change in future scenarios (the enhanced SRES scenarios proposed by Abildtrup et al. (2006)) using an optimising farm model (Annetts and Audsley, 2002) to define land profitability based, amongst other things, on the estimation of future crop yield using an relatively simple agro-climatic simulation model (Mayr et al., 1996). Results show that the effect of different climates is relatively small but that there are large variations with respect to the economic scenarios, and thereby there is a great uncertainty in future projections.

Some impact assessments combine an analysis using indicators with crop growth simulations. An example is the study reported in Semenov and Stratonovitch (2010), in which a multi-model ensemble of GCMs, downscaled using a weather generation approach, are used to project the range of temperatures that will occur at a mid-21st century horizon. In this study, the authors simultaneously simulated wheat crop growth using a process-based model (Sirius model as described in Jamieson et al. (1998)) and estimated the probability of occurrence of high stressing temperatures during anthesis[2]. The study only provides results for 4 punctual sites across Europe. Interestingly, they explain how wheat in a Southern site where higher temperature changes are projected might be less affected than in actual conditions because the advance in anthesis due to climate change might compensate the temperature increase since wheat will flower in a milder earlier season.

Such analysis can be potentially be expanded using the ELPIS dataset (Semenov et al., 2010), which is a dataset containing local-scale daily climate over Europe obtained by combining a weather generator trained over the European Crop Growth Monitoring System (CGMS) meteorological dataset and a multi-model ensemble of GCM simulations (from the ENSEMBLES project).

It must be noted that in the scientific literature authors also suggest to have a more integrated approach in climate-crop modelling in which the crop growth models would be embedded in the climate models (Betts, 2005; Hansen et al., 2006; Osborne et al., 2007). In this way, the effects of vegetation on climate could be integrated dynamically i.e. allowing a feedback from crop models towards the climatic system and thereby avoiding the effort required to transfer data (and associated errors and approximations) between two modelling systems. It must be noted, however, that the problem of downscaling from climate to resolutions adequate for crop model remains: it is internalised in the modelling framework.

[2] The flowering period during which damage from temperature may have a significant impact on yield

A point should be made on the fact that crop models generally simulate potential yields or yields limited by water or nutrient availability. These estimations do not always relate to observed yields because spatialised information concerning management strategies is not readily available. Some studies (e.g. Reidsma et al. 2009) seek to identify factors at the regional level that explain differences between observed and simulated yield.

2. Generation of weather data

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2.1. Introduction

Weather data is necessary to run crop simulations. To run them for projected climate change scenarios, the weather data has to be generated which is compatible with the requirements of crop models. AVEMAC is expected to base its analyses on data generated using regional climate models (RCM) nested in global circulation models (GCM), with a statistically adjusted bias-correction as implemented in accordance to the literature (Dosio and Paruolo, 2011). In fact, the need for bias correcting GCM-RCM projections for use by impact models is well known (e.g. Christensen et al., 2008), and the influence of such biases on hydrological and crop modelling has been extensively investigated by (e.g. Teutschbein and Seibert, 2010), who claimed that unless models' outputs are corrected, their application to impact models may be unrealistic.

2.2. Input climate data

The source of climate data for AVEMAC is the bias-corrected ENSEMBLES dataset of Dosio & Paruolo (2011). Since the project do not allow for an exhaustive use of all the GCM-RCM combinations within the ENSEMBLES dataset, priority has been given to the future projections of the A1B emission scenario given by the HadCM3 GCM nested with the HadRM3 RCM (the realization is denoted as METO-HC-HadRM3Q0-HadCM3Q0 in the ENSEMBLES project). This represents a "warm" realization of the A1B emission scenario. To compare the result with a milder scenario, AVEMAC also includes simulations based on another GCM, namely ECHAM5, coupled with the HIRHAM5 RCM for the downscaling. This can be considered as a "cold" realization (denoted DMI-HIRHAM5-ECHAM5 in the ENSEMBLES project). These two realizations of a single scenario are the extremes within the ones analysed in the ENSEMBLES project, allowing testing the largest uncertainty available in weather inputs to impact models. To simplify the notation throughout this report, these two realizations will be referred to either only using the shorter names of the driving GCMs, HadCM3 and ECHAM5, or simply as the "warm" and "cold" A1B realizations.

The time horizons that are explored in AVEMAC are 2020 and 2030, which are to be compared to a baseline of 2000. Therefore, given the two realizations (the "warm" based on HadCM3 and the "cold" based on ECHAM5), a total of six climate datasets are to be used for the crop simulations.

The two realizations of the emission scenario A1B were compared to the baseline period (1993-2007) data using the estimates available from the same scenarios of the same years. The comparison was made as frequencies in classes representing the range of variability for air temperature and rainfall, not being possible a 1:1 comparison between scenario realizations and data based on observations.

The reference weather data used were the Crop Growth Modelling System weather database, and the ECMWF. Both A1B realizations matched acceptably (qualitative, synthetic evaluation) the reference data series based on observations.

Although the A1B realizations were initially assumed to be ready for use, a closer analysis of the dataset by Dosio & Paruolo (2011) revealed that part of it remains inadequate to properly run process-based crop growth models to assess climate change impacts on yield in the framework of AVEMAC. There are two different problems to solve. The first problem relates to the lack of consistency of weather parameters, which results from the fact that the bias-correction is done on a subset of the necessary variables only, namely air temperature and rainfall. Other required variables, such as global solar radiation and wind speed, have unrealistic distributions when compared to observed data from the MARS-CGMS database or to simulated data from ECMWF over a past period of time. The second problem is a question of sample size with regards to the number of years needed to represent a specific time horizon (i.e. 2020, 2030 and the baseline). The methodological steps taken to solve both these problems are described in the following two sections.

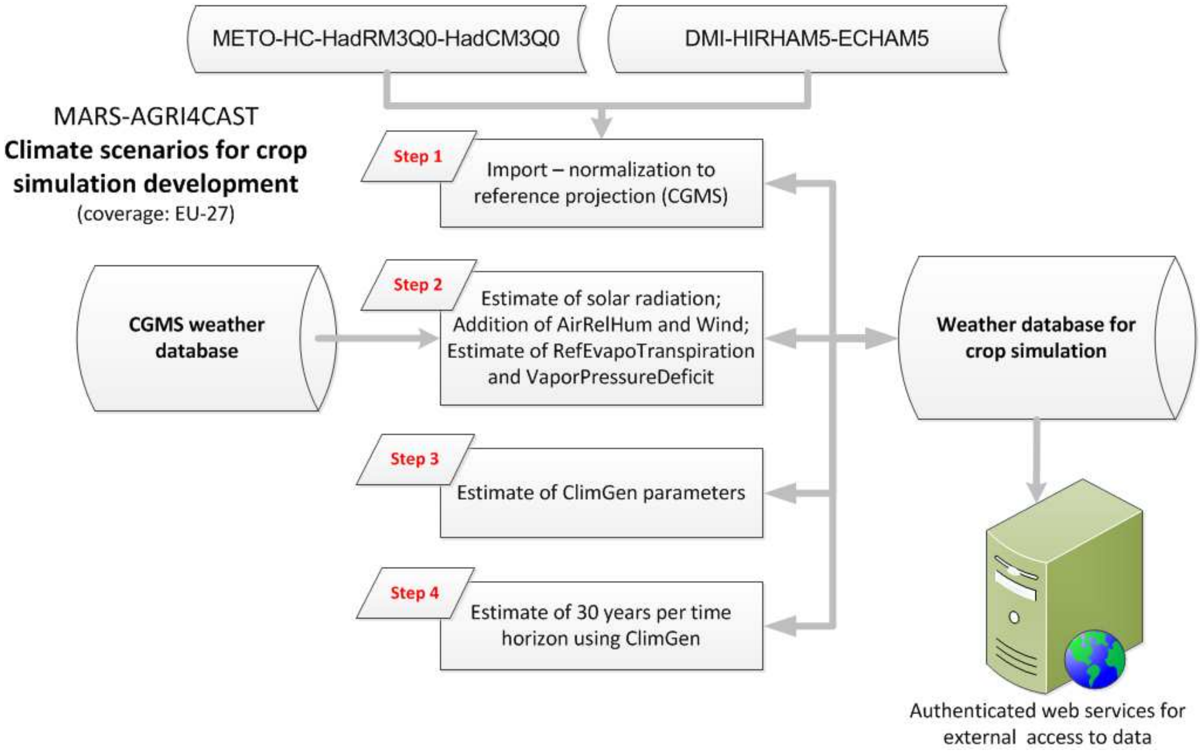


Figure 1: Outline of the processing of climate data.

2.3. Consistency of weather parameters

Crop simulation models require daily inputs of weather. A process-based crop simulation model can be very sensitive to weather inputs, not only as values, but also to consistency of the daily record. If data generation via downscaling is the result of an independent generation of weather variables, such consistency is not achieved. Also, if monthly mean values taken from GCM output are the basis for generating daily weather data, the resulting values do not necessarily represent observed or known patterns for the variable of interest: A monthly mean of rainfall can be spread over the whole month, or it can be concentrated in few rainfall events. Another example is solar radiation: From monthly averages that can be considered correct daily values might be derived which do not show the expected range of variation. Crop models are very sensitive to such differences, because of the time step considered, and because the processes they simulate are non-linear. The solution implemented to construct the AVEMAC weather datasets are described below for each variable.

Global solar radiation

Global solar radiation was estimated using the auto-calibration procedure (Bojanowski & Donatelli, *in preparation*) of the method Bristow-Campbell, which does not require reference data (i.e. recorded data of global solar radiation). The methods for estimating global solar radiation using daily air temperature range are based on the assumption that the site is not significantly affected by advection, which of course is not always the case. In case of an attempt to estimate the solar radiation pattern of a specific site, this assumption can be a strong limitation, but when working with abstractions such as interpolated time series associated to a spatial grid, the assumption can be considered non-limiting. This because the range based method is physically based: clear days show a greater range of temperature because during the days solar irradiance is not filtered by clouds, and, during the night, the long wave emission from soil surface is more rapidly lost in the atmosphere.
Also, seasonality is accounted for in the specific model. As described in the relevant paper, the auto-calibration method provides robust estimates of solar radiation, with the advantage of estimating a value, which is consistent with temperature data.

Given that scenarios of climate change as from GCM do estimate changes in temperature, the Bristow-Cambell *b* parameter is consequently estimated for each scenario, and solar radiation is estimated accordingly. Of course there are uncertainties on the temperature estimates of GCM and RCM, but it is out of scope of this application to articulate about this aspect; however, data integration is done creating data records which are consist at daily level, as required by crop models. Clear sky transmissivity was estimated for each grid cell from remote sensing data (Bojanowski & Donatelli, *in preparation*), prior to the estimate of the *b* parameter, being *c* kept constant as c=2.

Wind speed and air relative humidity

Global circulation models do not produce estimates of either wind or air relative humidity.

A conservative approach is to use historical series of such data, which only empirically can be associated, in general with a weak relationship at each site, to patterns of temperature and rainfall.

However, the data to investigate such relationships are certainly not available for future climate scenarios, hence the conservative choice of using unchanged historical measurements was made. The measurements used are provided by the CGMS weather database: the data of 1996-2005 were used both for the baseline and future scenarios.

Reference evapotranspiration and vapour pressure deficit

Reference evapotranspiration and vapour pressure deficit were estimated from the variables above using the FAO56 method, as implemented in the CLIMA libraries (Donatelli et al., 2006, 2009).

A simpler method could have been chosen given the uncertainty on inputs, but given that no reference data is available, a more physically based model as Penman-Monteith was preferred to empirical models which would have generated data not necessarily consistent with other variables. Furthermore, an empirical model was not an option given no reference data to estimate its parameters.

2.4. Sample size

The time series produced via GCM (or RCM) runs represent the trends expected in climate variables such as temperature; however, there is a random component of variability around such a trend. For a given time horizon, climate studies will typically look at a sample of 30 years around that horizon to characterise a given variable or to derive other data (such as crop yields) from it. Such sample size is deemed large enough so that the short-term random fluctuations – such as daily weather variations – do not influence the outputs derived from the GCM simulations. Having a large sample size is also a reason why climate studies typically look at time horizons that are well separated in time, e.g. 2020, 2050 and 2100, so that the trend effect dominates over the random noise of the yearly weather (which can take values which are much different from the trend).

In the case of AVEMAC, the time horizons of interest are 2020 and 2030. Taking windows of 30 years around these two horizons would result in an overlap that renders the separation into two horizons meaningless. When considering only 10 years (thereby avoiding overlap) the sample size becomes too small in order to assume that short-term weather fluctuations do not dominate over the trend. Indeed, three or four years, which are much warmer than the trend during a period of 10 years, will have stronger consequences on the average indicators of the crop simulations than if these years occurred within a period of 30 years.

A stochastic weather generator, ClimGen (Stöckle et al., 2001), was used to increase the sample size corresponding to each horizon. A set of 15 years from the GCM-RCM runs was used around each reference year (e.g. 2020 +/-7 years, so from 2013 to 2027), increasing the robustness of the estimate to characterize a time period. The weather generator uses these data to derive monthly parameters resuming the distribution of each weather variable for each grid cell. These parameters are then used to generate a set of 30 synthetic years for every grid cell, which have the characteristics of the 15-year period. Although the 15-year periods, used as source to generate parameters, overlap by 4 years across the time spans centred on the dates of interest, this is not a problem since the new synthetic years are different (although referred to the same weather) from the GCM-RCM ones.

It must be noted that the weather generator is applied independently on every grid cell based on parameters defined for every grid cell individually. As a result, there is an apparent loss of spatial consistency of weather variables if a single synthetic year is considered for all cells. However, each of the 30 years generated is a sample of weather data for that period and cannot be paired to individual years of adjacent cells. The spatial consistency is ensured when averaging the 30 years, thus observing the mean weather parameters. This argument applies also to variables of indicators derived from this synthetic dataset. The final crop simulation results are therefore based on 30 different runs for each time horizon, and must be considered as possible outcomes for the considered period.

2.5. Description of the generated weather

After corrections and calculation mentioned above, the AVEMAC dataset is composed of the following variables:

Table 1. Weather parameters

Variable	Units	Description
Air temperature maximum	°C	Maximum air temperature
Air temperature minimum	°C	Minimum air temperature
Rainfall	mm	Precipitation
Global solar radiation	kJ/m2	Global solar radiation at earth surface
Air relative humidity maximum	%	Air relative humidity maximum
Air relative humidity minimum	%	Air relative humidity minimum
Wind speed	m/s	Wind speed
Reference evapotranspiration (FAO56)	mm	Reference evapotranspiration
Vapour pressure deficit	kPa	Vapour pressure deficit

A version of an aridity index is also computed based on precipitation and evapotranspiration. It is defined as:

$$AridityIndex = \frac{\sum rain - \sum ET_0}{\sum rain + \sum ET_0}$$

Positive values indicate water availability in theory greater than demand; 0 indicates that rainfall and evapotranspiration balance.
The following maps provide a description of the differences of generated weather variables and indices between horizons (2020, 2030 vs. 2000 baseline) and between the same realizations done with different GCMs (HadCM3 vs. ECHAM5). The maps resume information for 6-month periods for "colder" and "warmer" seasons (respectively October to March and April to September). For each of the weather variables, maps show the difference with respect to the baseline in terms difference between means. 2020 and 2030 are shown with respect to the baseline of the corresponding realization of A1B (HadCM3 and ECHAM5 baselines not being identical). Also, difference maps of HadCM3 and Echam5 for 2020 and 2030 are presented to compare the two realizations of the A1B SRES. The geographical edges of the downscaling via RCM may present artefacts, which do not impact on the analysis targeting at EU27 coverage.

Horizon 2020 under A1B scenario with HadCM3

When comparing the expected climate change with HadCM3 under the A1B scenario in 2020 with 2000, the intensity in the rise of temperature (for both minima and maxima) follows a clear gradient from North-East to South-West, especially in the cold season (October to March). The far North could see rises in minimum temperature by as much as 3°C; most of central and Eastern Europe can expect warmer winters whereas there is little change in the Iberian Peninsula. In spring and summer, the gradient is not so evident since (mild) rises in temperature seem limited to the Atlantic coast for most of EU-27. Some parts of Italy even see lower temperatures than in the baseline. However, the European part of Russia and Finland are expected to see a much stronger rise in summer temperature.

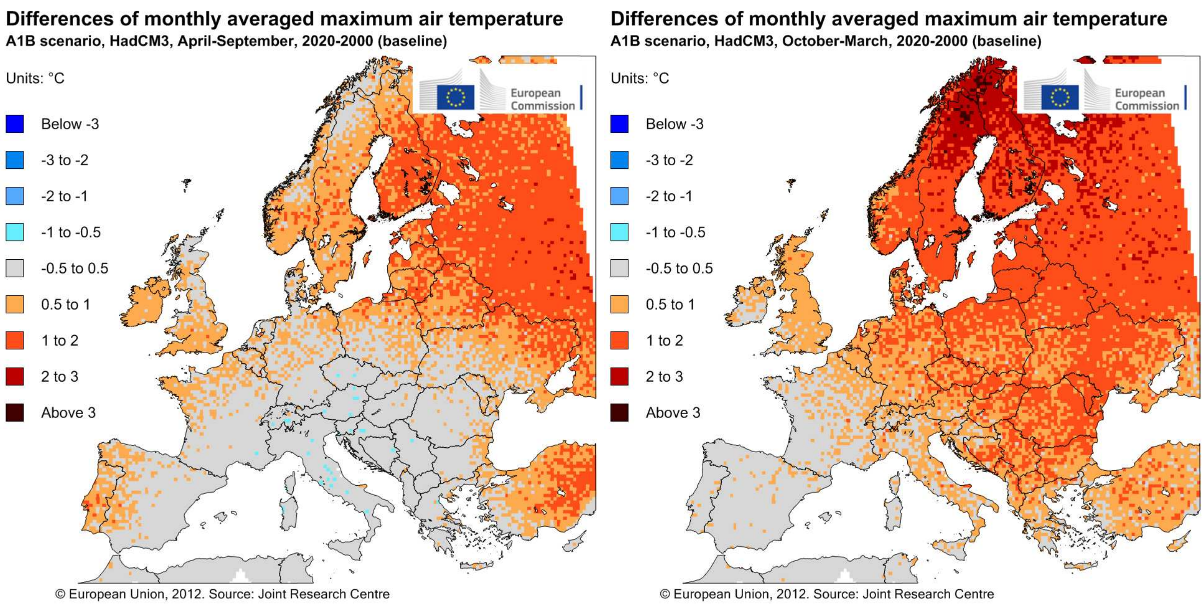


Figure 2. Difference of monthly averaged maximum temperature (HadCM3, A1B, 2020-2000) for April-September (left) and October-March (right)

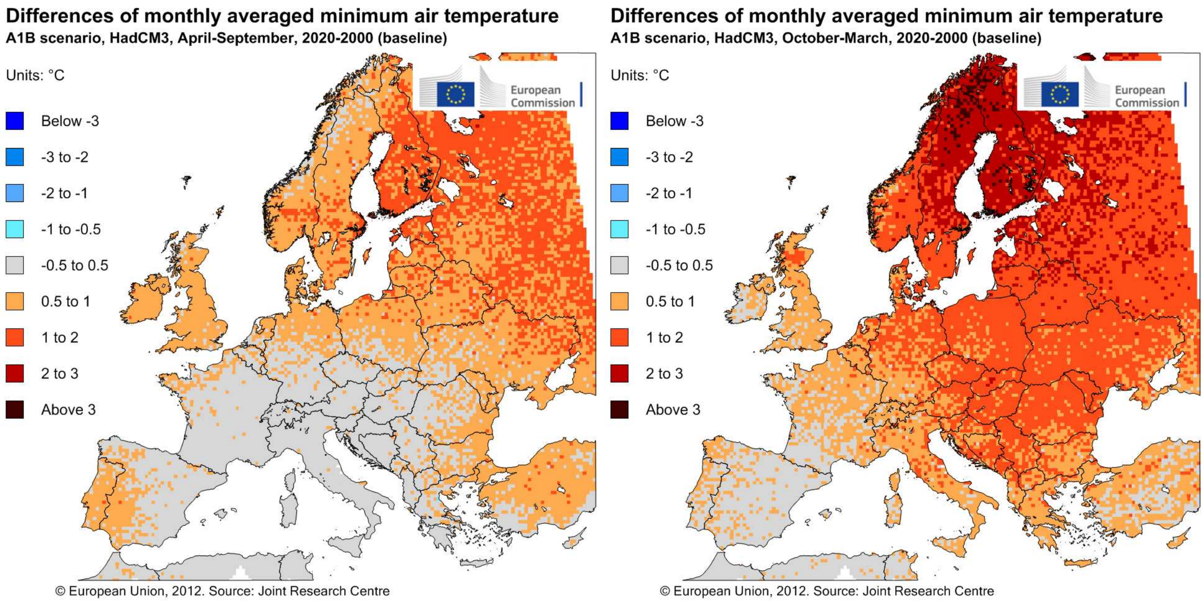


Figure 3. Difference of monthly averaged minimum temperature (HadCM3, A1B, 2020-2000) for April-September (left) and October-March (right)

Changes in the precipitation regime are dominated by a strong increase in cumulated rain over a zone centred south of the Alps and which in summer extends to the entire Italian peninsula and the Balkans. Scandinavia and the British Isles also expect higher rainfall, especially in summer. Precipitation increases also in southern Spain and Portugal during winter while the northern part of the peninsula will have less cumulated rainfall than in the baseline for the same period.

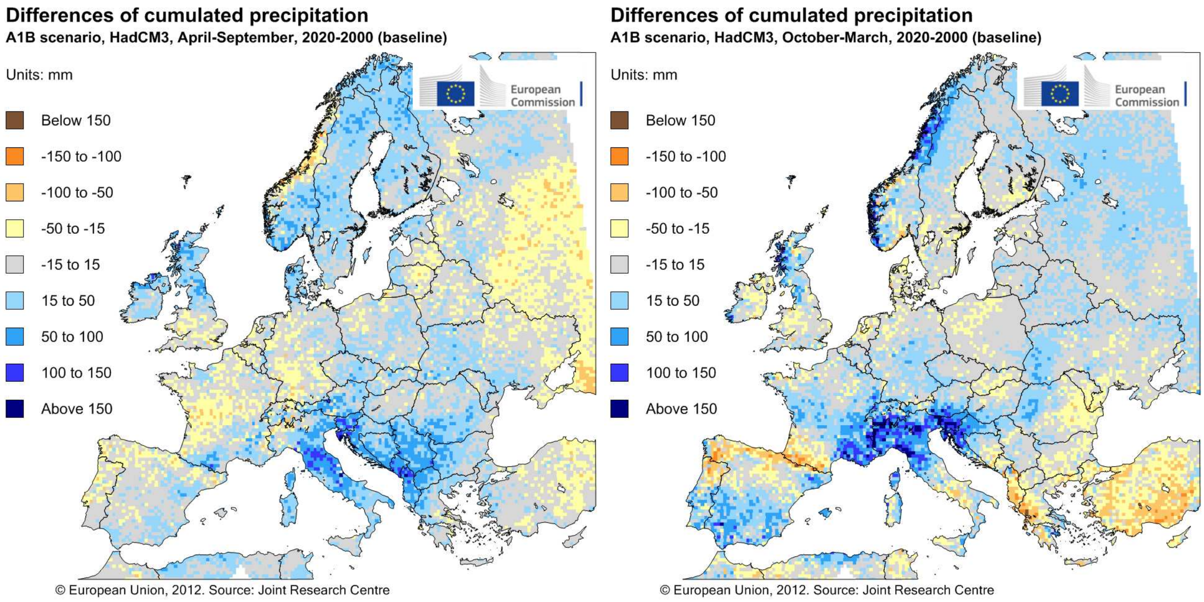


Figure 4. Difference of cumulated precipitation (HadCM3, A1B, 2020-2000) for April-September (left) and October-March (right)

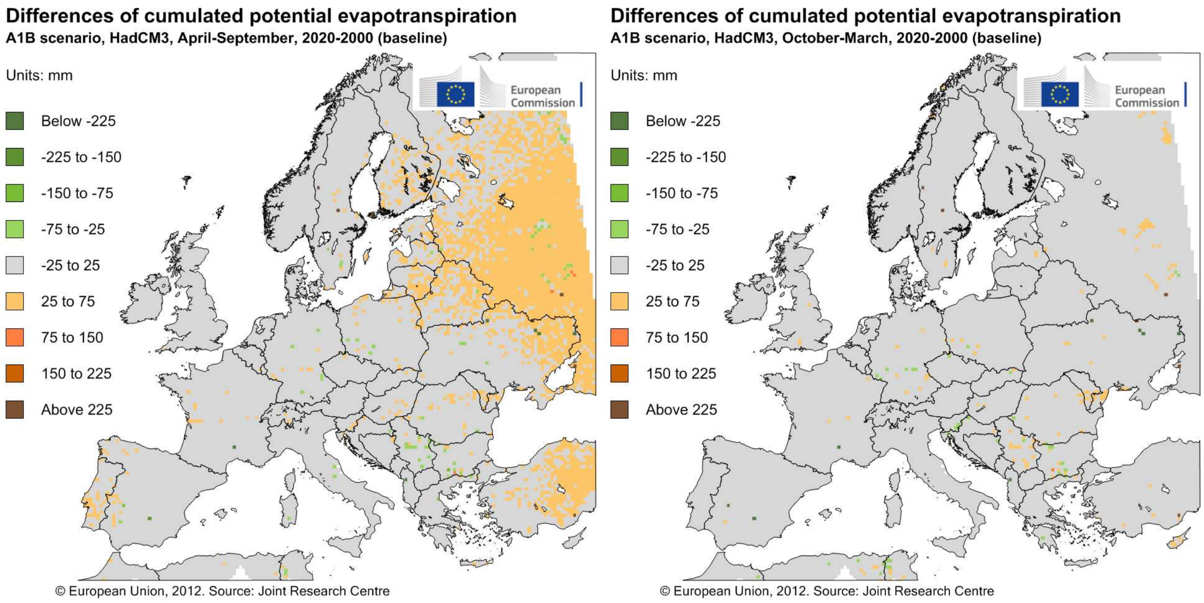


Figure 5. Difference of cumulated potential evapotranspiration (HadCM3, A1B, 2020-2000) for April-September (left) and October-March (right)

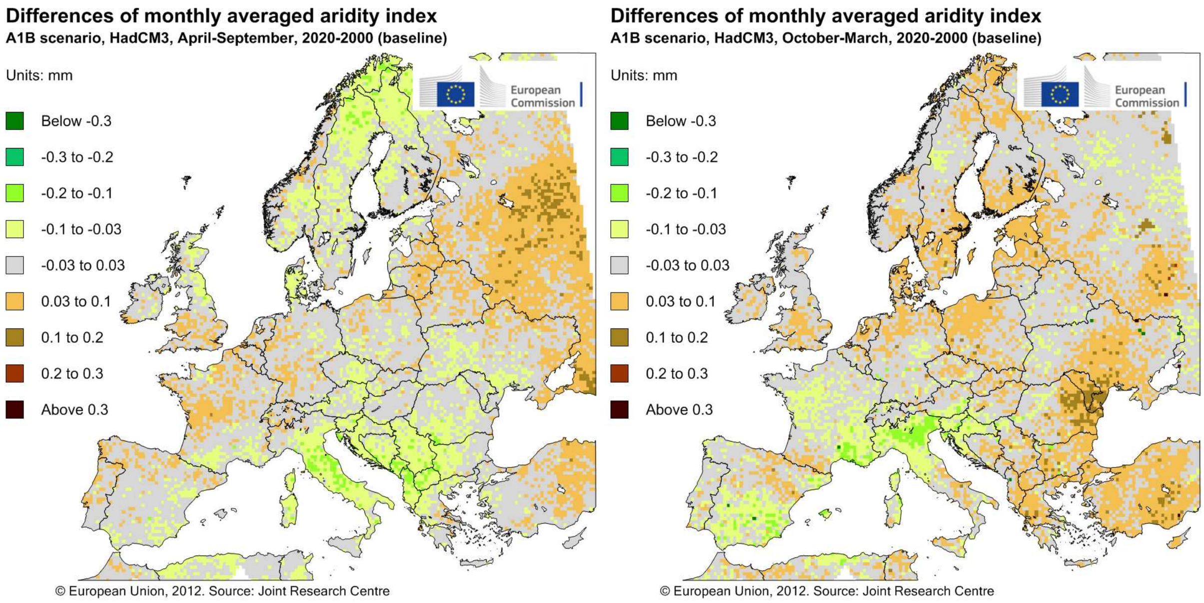


Figure 6. Difference of monthly average aridity index (HadCM3, A1B, 2020-2000) for April-September (left) and October-March (right)

As expected, the calculated potential evapotranspiration does not change much since it is calculated based on the same wind data for both 2000 and 2020. Some increase in evapotranspiration is seen over Russia during summer driven by the stronger increase in temperature. This is translated in higher aridity, as shown on the Aridity Index map, which otherwise reflect the changes in the precipitation regime.

Horizon 2030 under A1B scenario with HadCM3

The projections of the HadCM3 (A1B scenario) for 2030 involve an increase in temperature, which is marked over the entire continent and for both seasons (practically all of Europe is now at least 0.5°C above the corresponding temperature in 2000). The rise is higher for maximum temperature in summer and for minimum temperature in winter. With the exception of Scandinavia and the British Isles, European summers are considerably drier in 2030 than in 2020 and 2000. The notable increase in cumulated rainfall around the Italian peninsula disappears in summer but remains in winter. The region comprising Northern Spain and South-Western France which is drier in winter in 2020 becomes even drier in 2030 and extends geographically.

Changes in cumulated potential evapotranspiration remain marginal in winter, but increase slightly throughout Europe (except in Scandinavia, British Isles and Northern Atlantic coast). It must be acknowledged that there is apparently a calculation artefact in the cumulated potential evapotranspiration difference map for summer: a horizontal strip going from West to East through Switzerland, Austria, Hungary and Romania. The impact of this artefact is deemed to be insignificant on the biophysical simulations and the source of it has to be further investigated.

The Aridity Index essentially reflects the change in precipitation, indicating conditions of water availability degrade in high producing countries such as France, Germany and Poland.

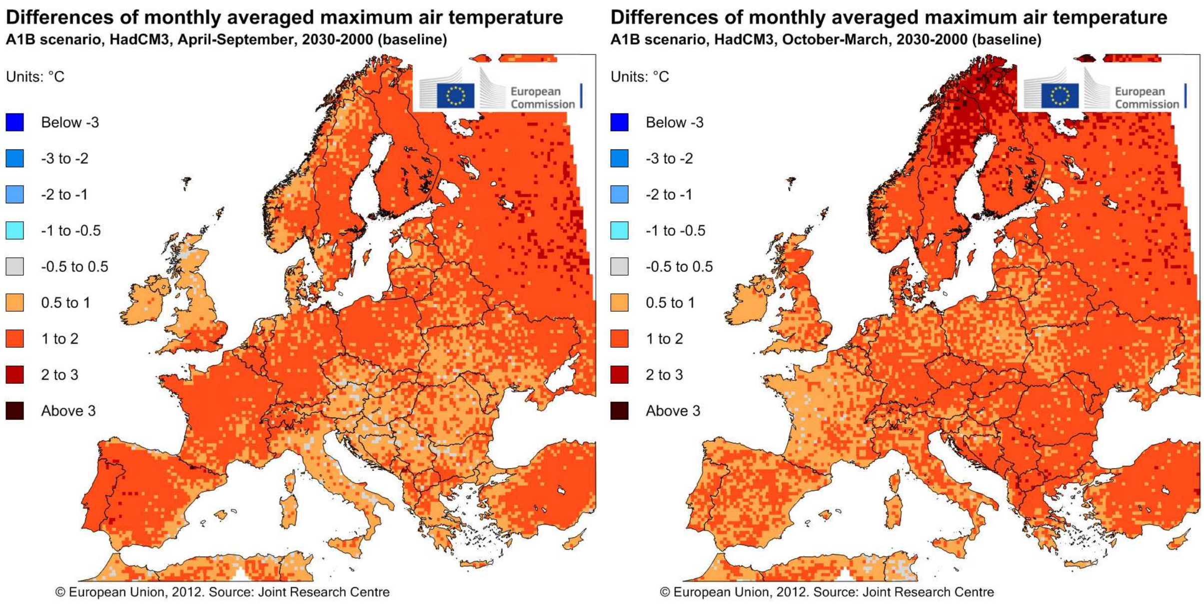


Figure 7. Difference of monthly averaged maximum temperature (HadCM3, A1B, 2030-2000) for April-September (left) and October-March (right)

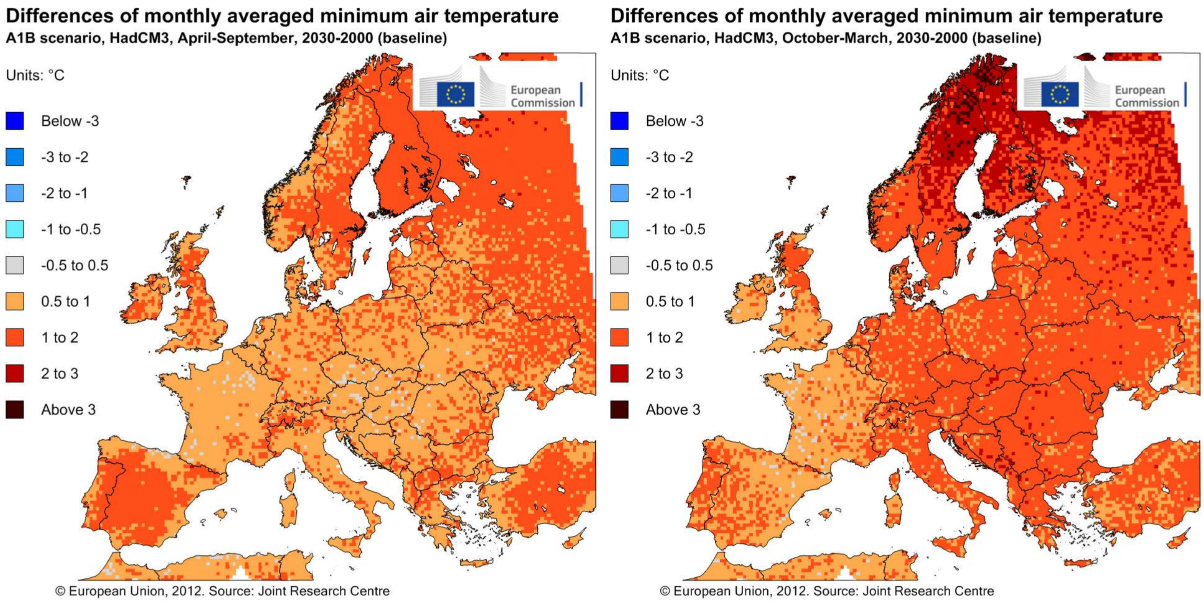


Figure 8. Difference of monthly averaged minimum temperature (HadCM3, A1B, 2030-2000) for April-September (left) and October-March (right)

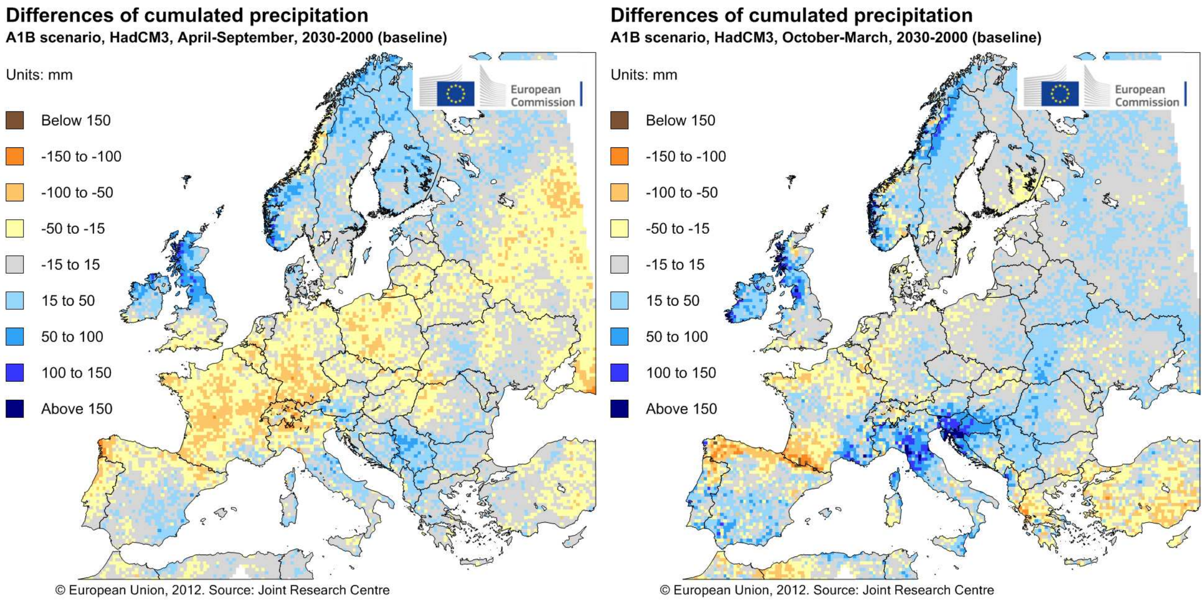


Figure 9. Difference of cumulated precipitation (HadCM3, A1B, 2030-2000) for April-September (left) and October-March (right)

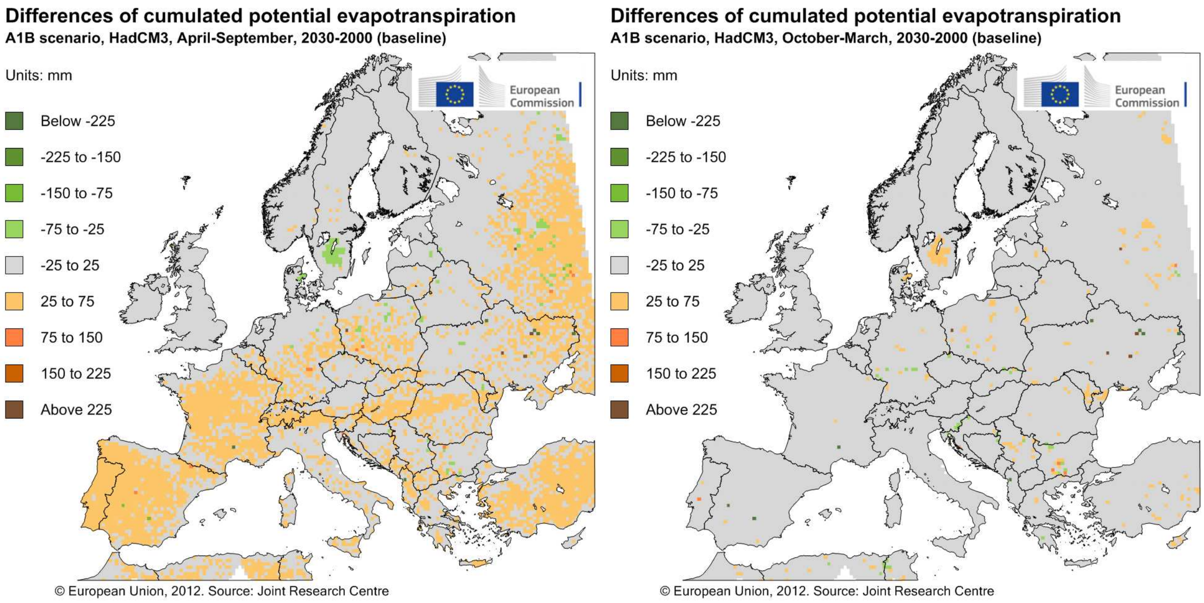


Figure 10. Difference of cumulated potential evapotranspiration (HadCM3,A1B, 2030-2000) for April-September (left) and October-March (right)

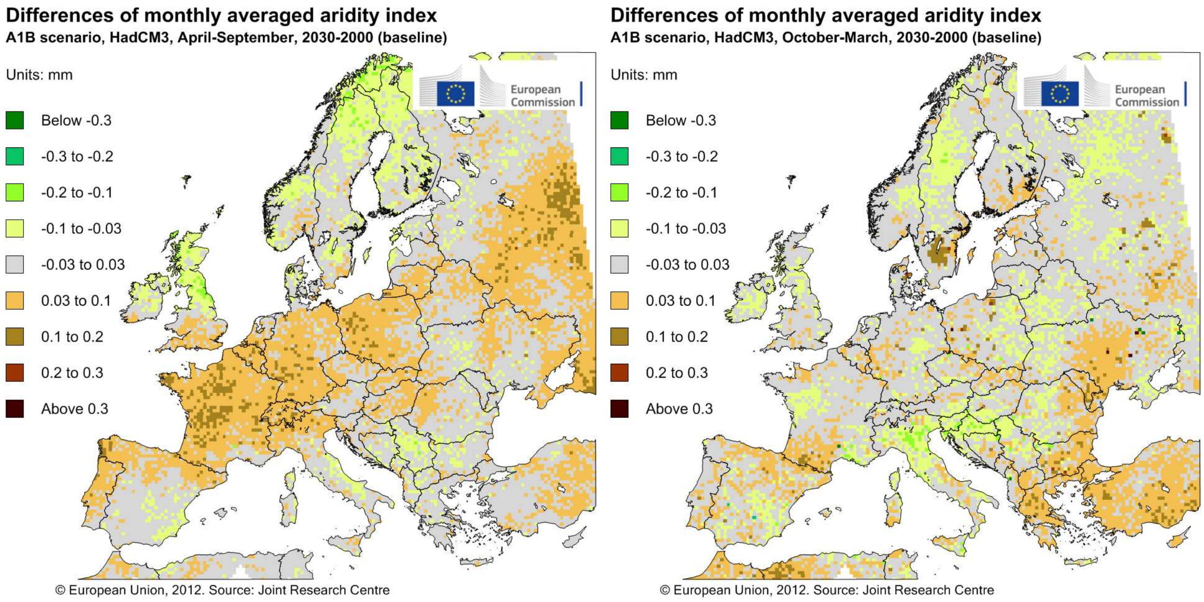


Figure 11. Difference of monthly average aridity index (HadCM3, A1B, 2030-2000) for April-September (left) and October-March (right)

Horizon 2020 under A1B scenario with ECHAM5

ECHAM5 projects for 2020 only a mild increase in minimum and maximum air temperature during the main crop-growing season (April to September) with sporadic patterns throughout Russia, Central and Eastern Europe. Only the maximum temperature over the Iberian Peninsula shows a consistent spatial pattern of increase, whereas some decrease in maximum temperature is also seen in Ireland. During the period from October to March, cooler minimum and maximum are projected by ECHAM5 over Scandinavia, Scotland and over sporadic cells in central and Eastern Europe. Over Russia, temperature rises even during this cold period.

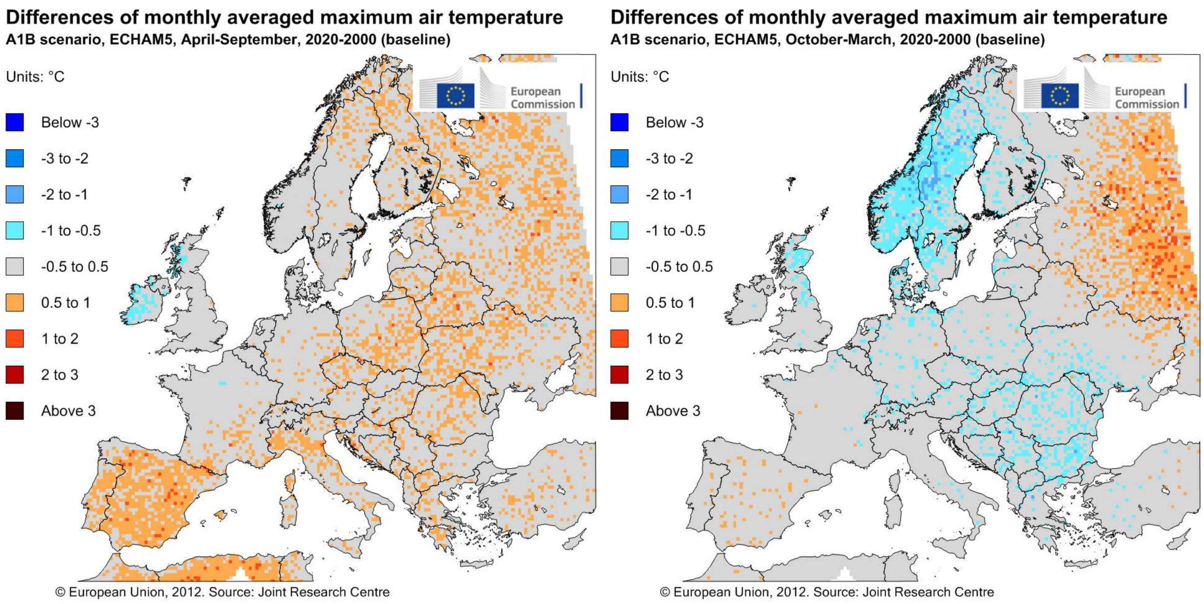


Figure 12. Difference of monthly averaged maximum temperature (ECHAM5, A1B, 2020-2000) for April-September (left) and October-March (right)

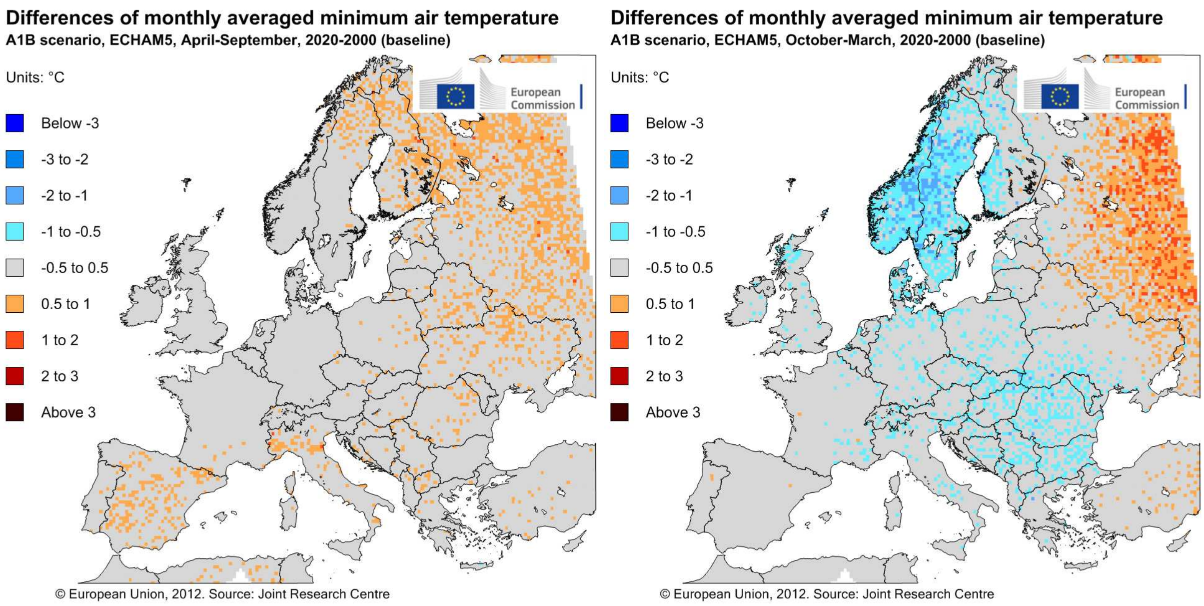


Figure 13. Difference of monthly averaged minimum temperature (ECHAM5, A1B, 2020-2000) for April-September (left) and October-March (right)

Overall, the precipitation regime does not change dramatically. The Iberian Peninsula and Western Europe do get drier growing seasons while Scandinavia and France are wetter. Notable exceptions include, during the cold season, a strong increase in precipitation in some mountain areas, such as the Western Alps, Pyrenees and Galicia, and a strong reduction of precipitations of the Western coast of Scandinavia.

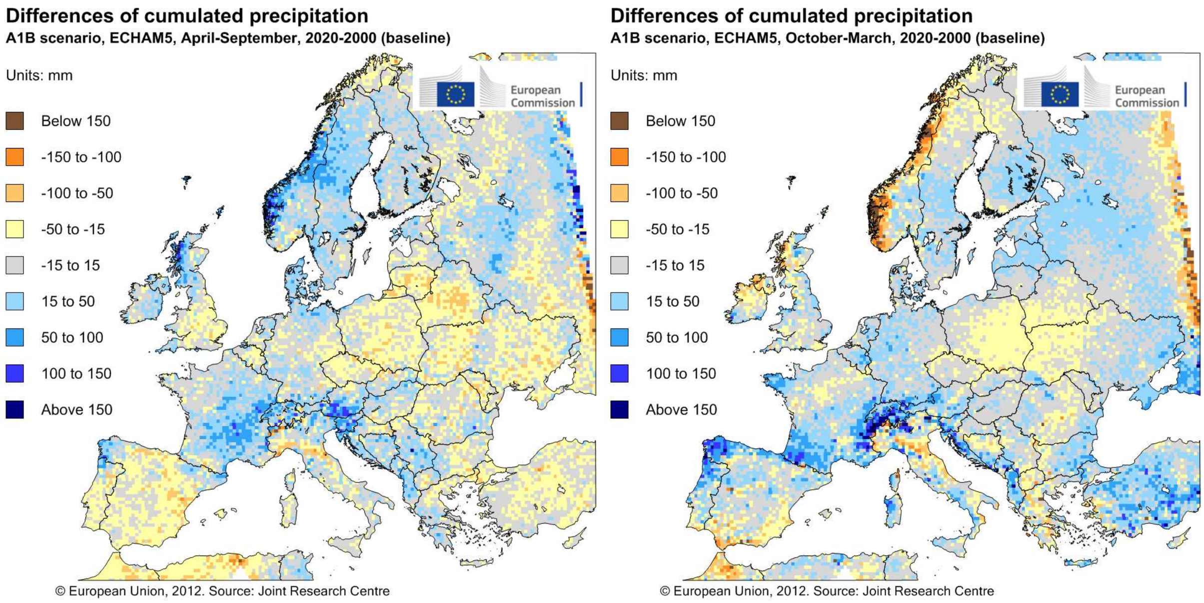


Figure 14. Difference of cumulated precipitation (ECHAM5, A1B, 2020-2000) for April-September (left) and October-March (right)

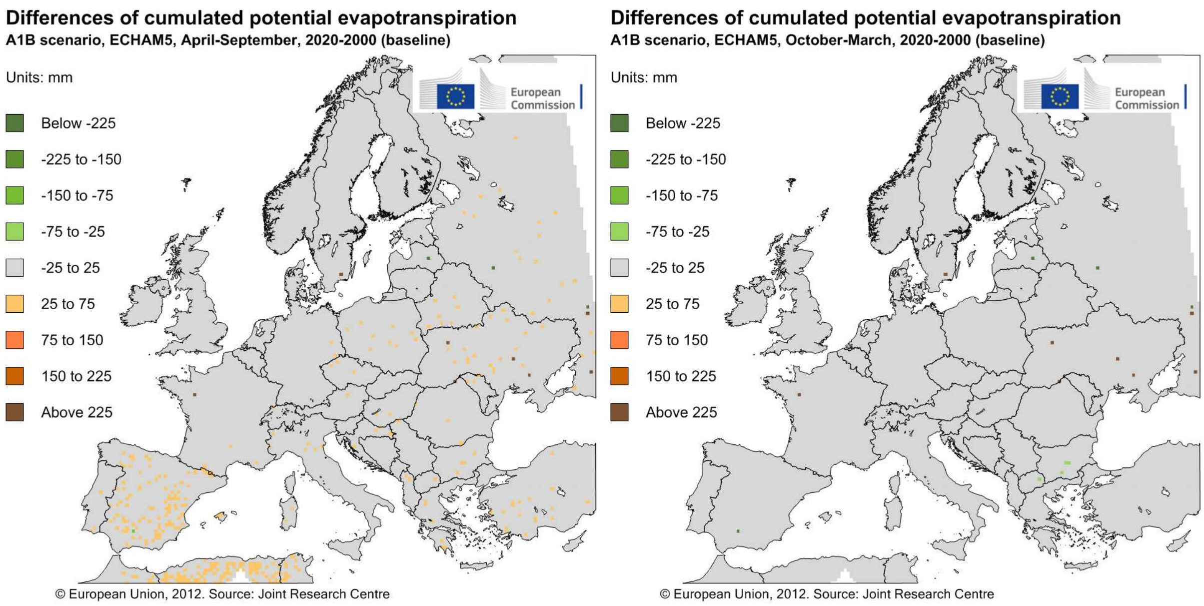


Figure 15. Difference of cumulated potential evapotranspiration (ECHAM5, A1B, 2020-2000) for April-September (left) and October-March (right)

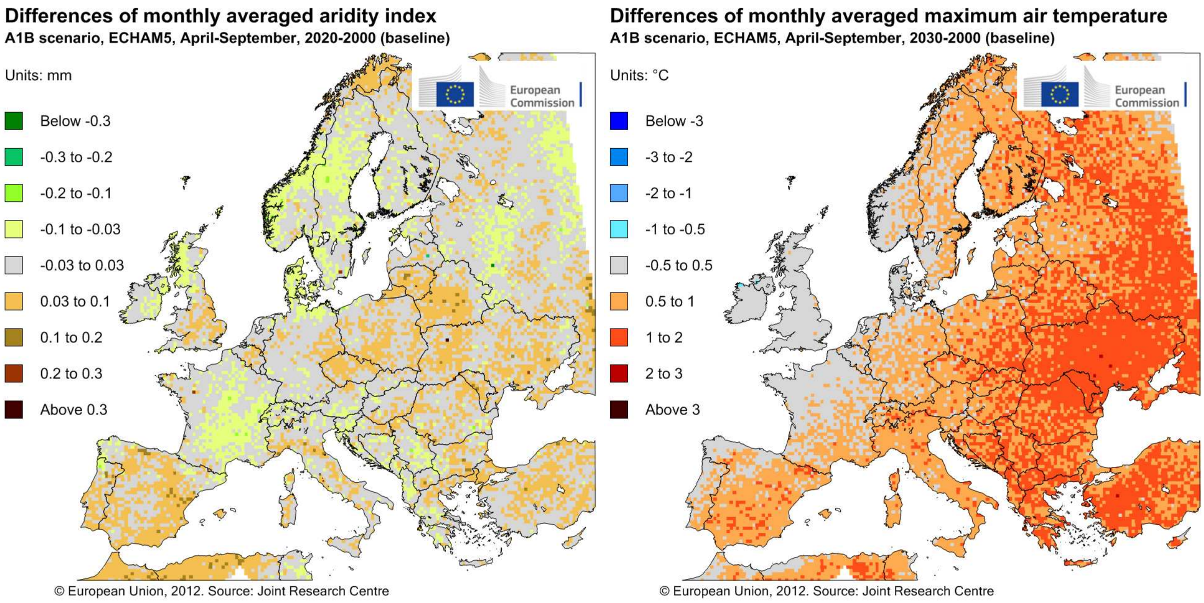


Figure 16. Difference of monthly average aridity index (ECHAM5, A1B, 2020-2000) for April-September (left) and October-March (right)

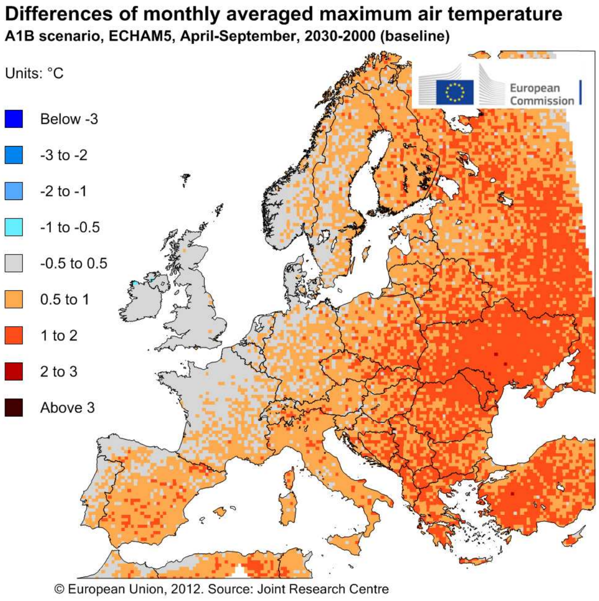
Since cumulated evapotranspiration does not change with respect to baseline (for the same reasons of no change in wind patterns), the changes in Aridity Index follow the same patterns as precipitation.

It must be stated that in the ECHAM5 simulations of precipitation (and on variables derived from it, such as Aridity Index) there are some artefacts coming that are visible and that are present in the ENSEMBLES input data. This mostly includes a line of unrealistic precipitation values along the easternmost border of the study area, and along the southern border of the study area in the south Maghreb.

Horizon 2030 under A1B scenario with ECHAM5

The 2030 projections from ECHAM5 indicate that in the period of April to September, only the British Isles and to some extend North-western Europe (France, Benelux, Denmark and Germany) are spared from increases in minimum and maximum temperatures. A generalise rise in temperature is also projected in the colder months, with a strong rise in continental Russia.

Precipitation increases strongly in France and to a lesser extent in Northern Europe during the cold period, while the warm period is drier than baseline (with the exception of Northern Italy and Scandinavia). Stronger evapotranspiration is expected in Eastern Europe in summer, which combined with drier conditions increase the aridity significantly.



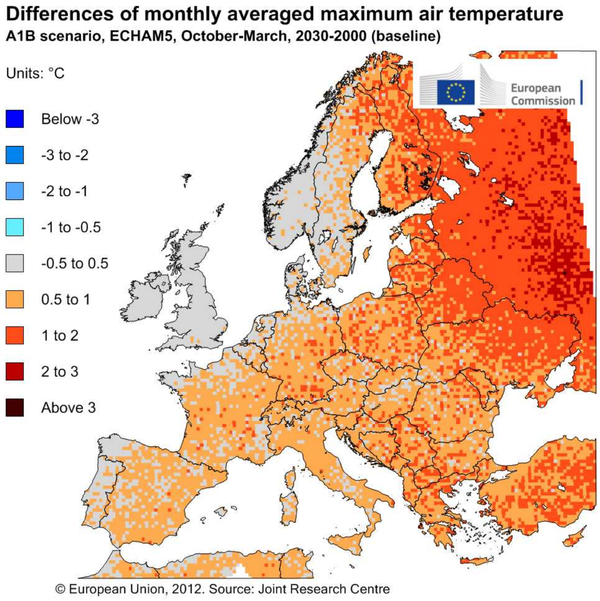
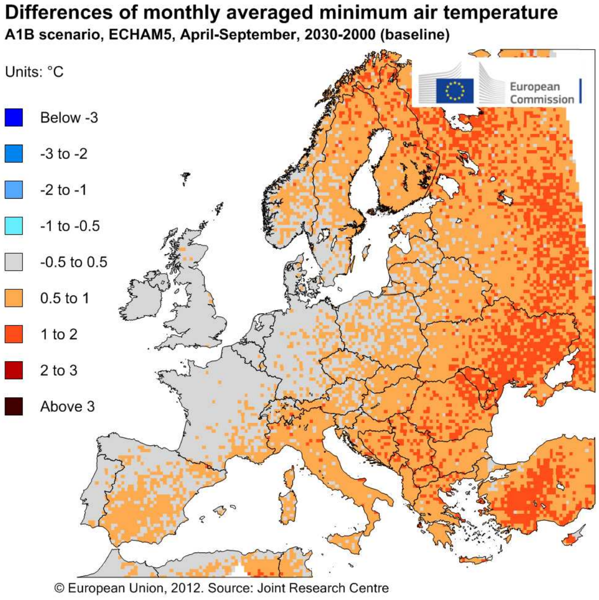


Figure 17. Difference of monthly averaged maximum temperature (ECHAM5, A1B, 2030-2000) for April-September (left) and October-March (right)



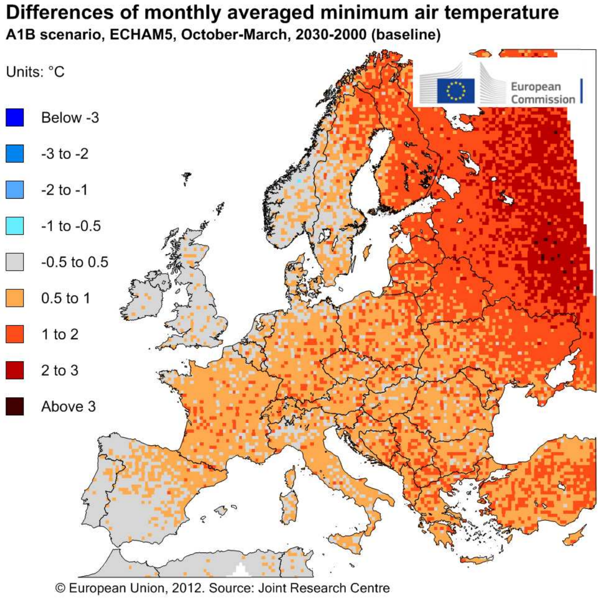


Figure 18. Difference of monthly averaged minimum temperature (ECHAM5, A1B, 2030-2000) for April-September (left) and October-March (right)

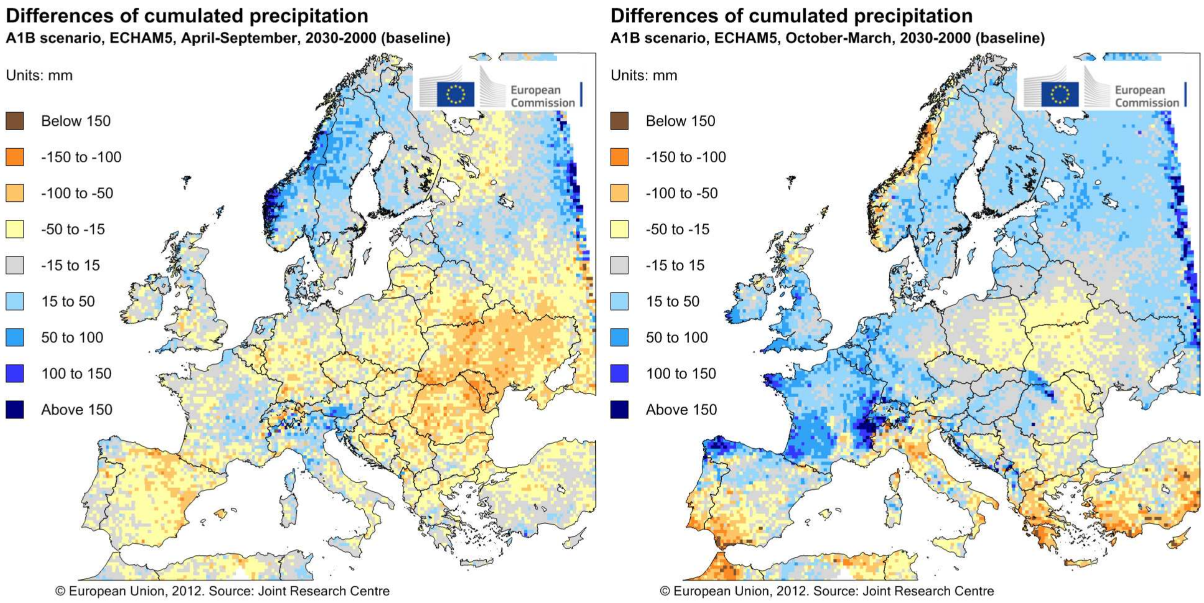


Figure 19. Difference of cumulated precipitation (ECHAM5, A1B, 2030-2000) for April-September (left) and October-March (right)

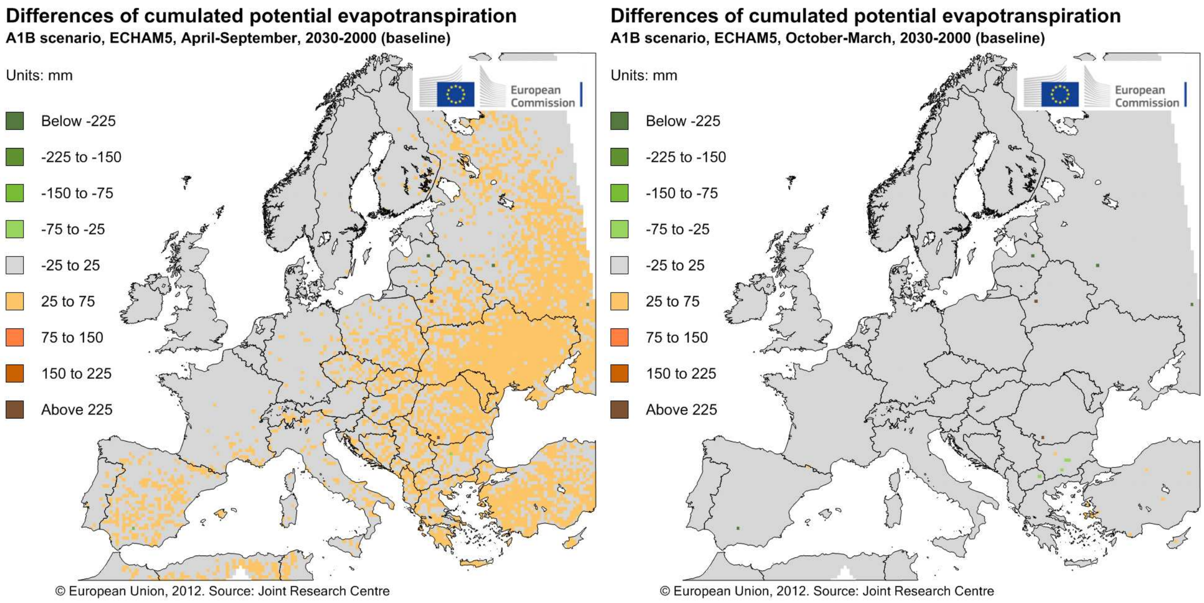
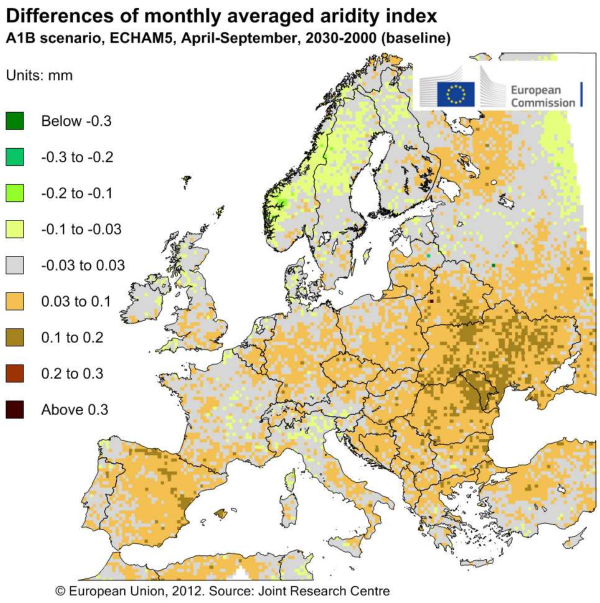


Figure 20. Difference of cumulated potential evapotranspiration (ECHAM5, A1B, 2030-2000) for April-September (left) and October-March (right)



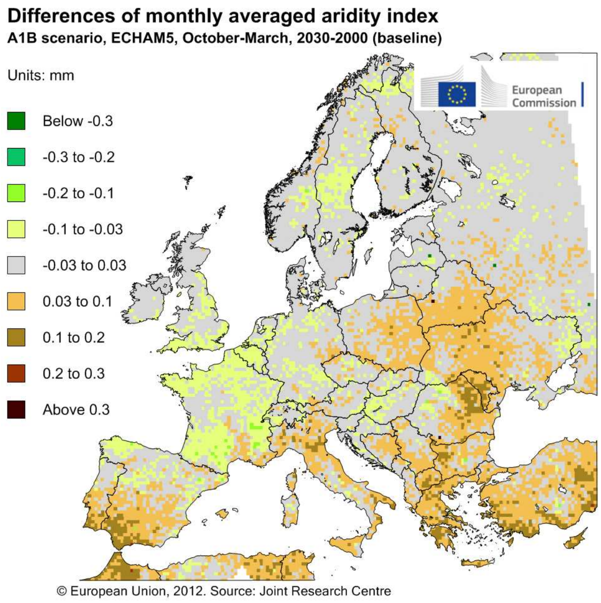


Figure 21. Difference of monthly average aridity index (ECHAM5, A1B, 2030-2000) for April-September (left) and October-March (right)

Comparison of HadCM3 and ECHAM5 for A1B 2020 horizon

The following maps describe the differences in the characterisation of the 2020 horizon between the two models: HadCM3 and ECHAM5. Maps display the difference of variables simulated with HadCM3 minus ECHAM5. As initially stated, HadCM3 provides a generally warmer picture than that of ECHAM5 since they represent correspondingly the upper and lower envelope of the ENSEMBLES dataset in terms of increases in temperature. The exception is the Iberian Peninsula, which both models seem to project similar changes at all seasons, and the easternmost part of the covered area during the cold season. Precipitation patterns change considerably from model to model, but overall HadCM3 is drier; however, the difference in Southern Europe for rainfall, where water availability is absolutely critical for rain-fed crops, appears very important. Evapotranspiration is also much stronger with HadCM3 from April to September almost everywhere (except in Portugal, Spain, Italy and Southern France). Being the difference in air temperature modest, the projection of the two realizations of the A1B differs substantially because of rainfall.

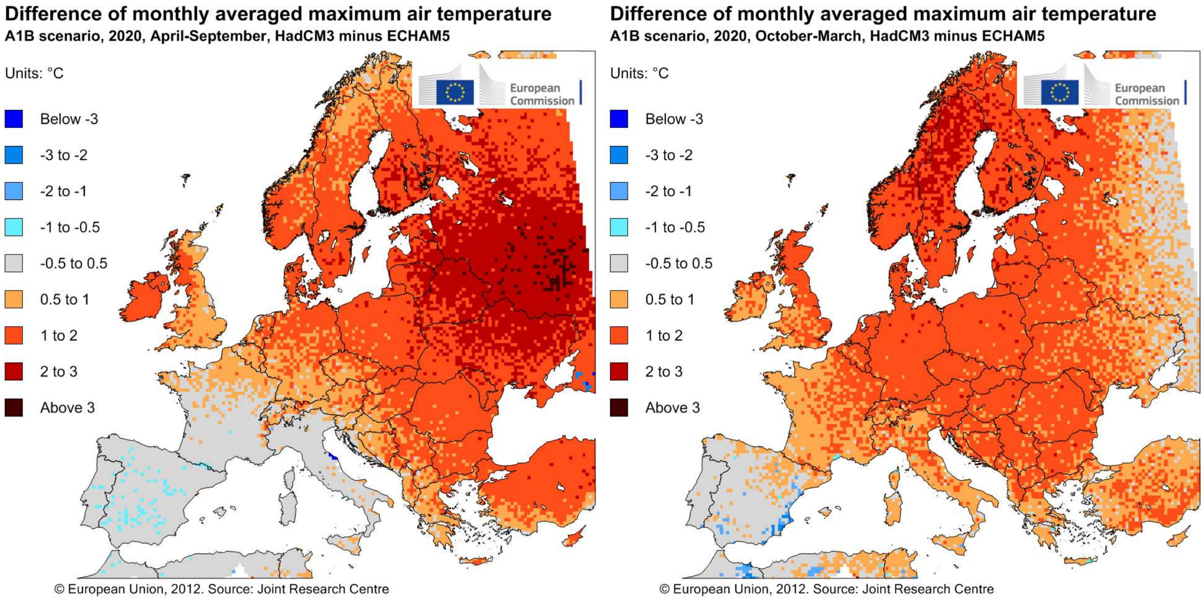


Figure 22. Difference of monthly averaged maximum temperature (HadCM3-ECHAM5, A1B, 2020) for April-September (left) and October-March (right)

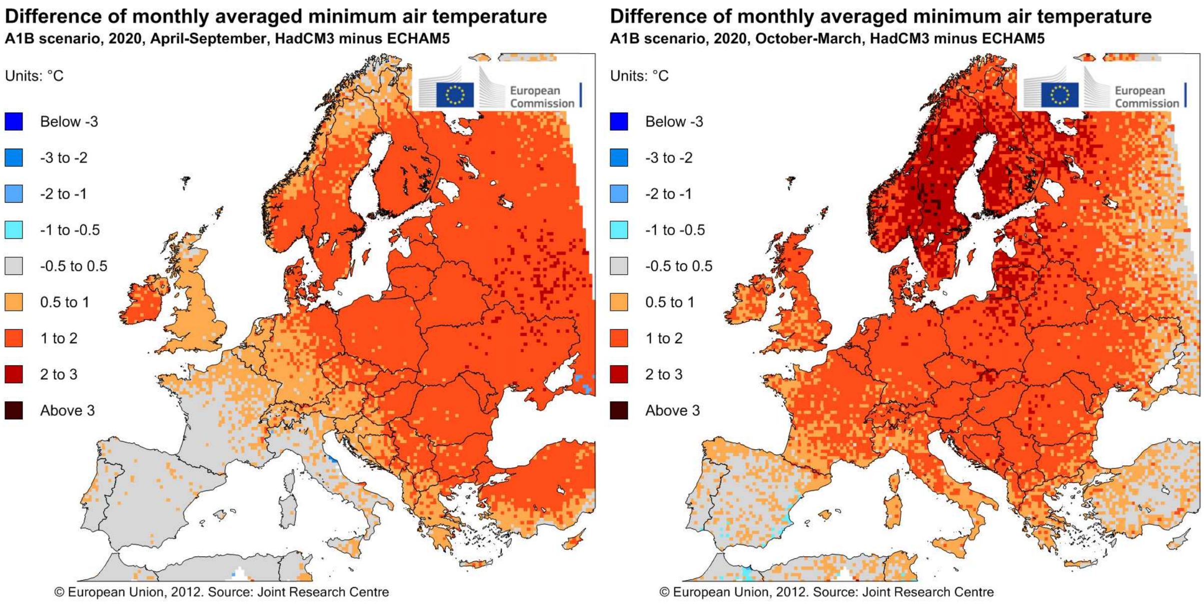


Figure 23. Difference of monthly averaged minimum temperature (HadCM3-ECHAM5, A1B, 2020) for April-September (left) and October-March (right)

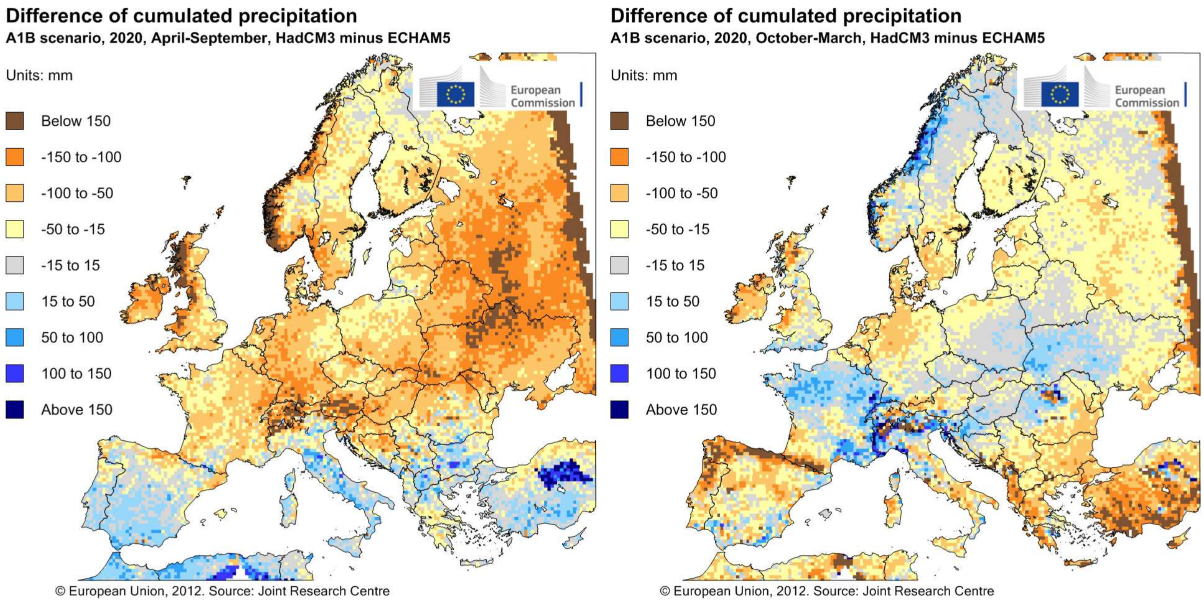


Figure 24. Difference of cumulated precipitation (HadCM3-ECHAM5, A1B, 2020) for April-September (left) and October-March (right)

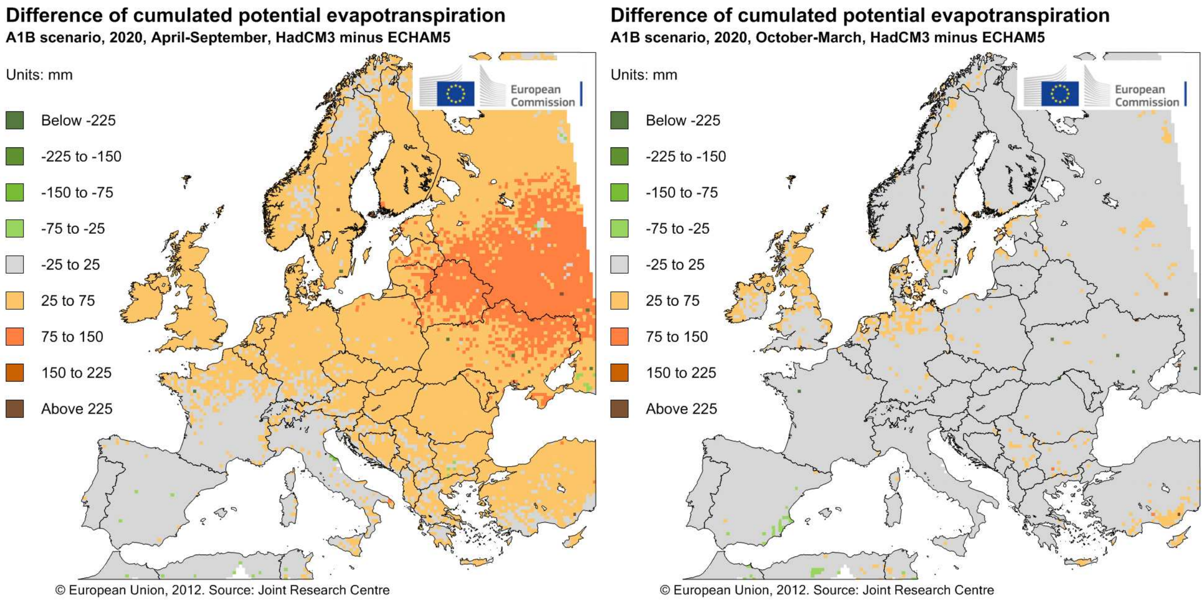


Figure 25. Difference of cumulated potential evapotranspiration (HadCM3-ECHAM5, A1B, 2020) for April-September (left) and October-March (right)

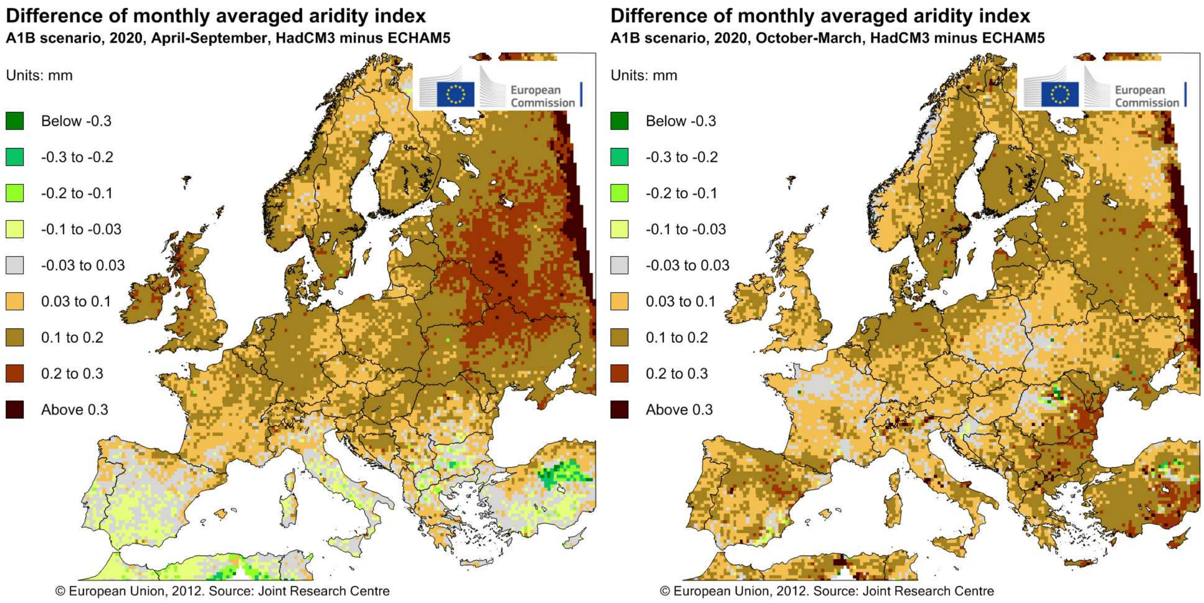


Figure 26. Difference of monthly average aridity index (HadCM3-ECHAM5, A1B, 2020) for April-September (left) and October-March (right)

Comparison of HadCM3 and ECHAM5 for A1B 2030 horizon

The changes between the warm A1B realization of HadCM3 and the cold one of ECHAM5 generally follow the same patterns in 2030 than in 2020. In the warm period of the year (April to September) HadCM3 provides a warmer and, with the exception of Spain (and, to a lesser extent, in the other areas of Southern Europe), drier situation than ECHAM5. In winter, temperature differences between the two models are milder and there is a reversal for Russia where ECHAM5 is providing a warmer picture than HadCM3. There is no difference in Evapotranspiration but the overall result is still that Europe in 2030 is more arid with HadCM3 than ECHAM5.

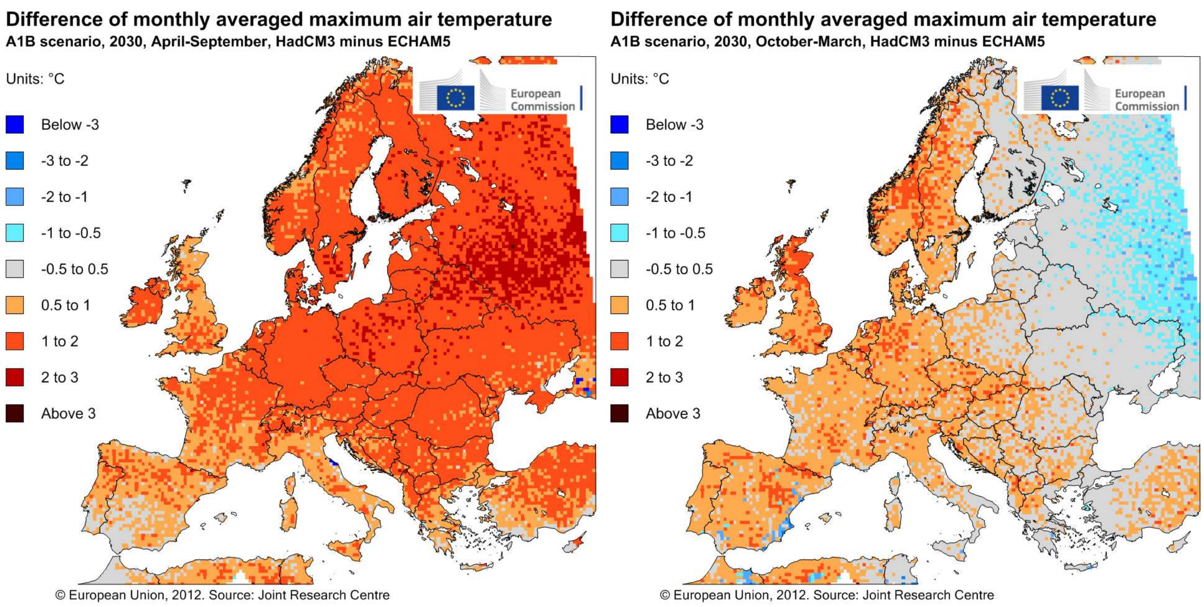


Figure 27. Difference of monthly averaged maximum temperature (HadCM3-ECHAM5, A1B, 2030) for April-September (left) and October-March (right)

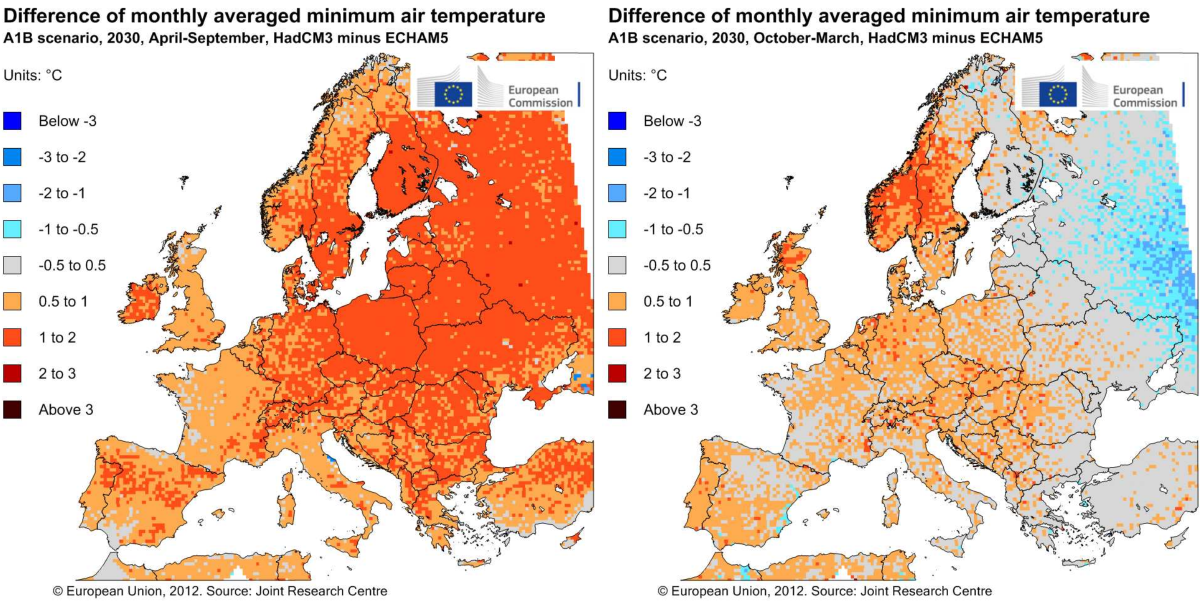


Figure 28. Difference of monthly averaged minimum temperature (HadCM3-ECHAM5, A1B, 2030) for April-September (left) and October-March (right)

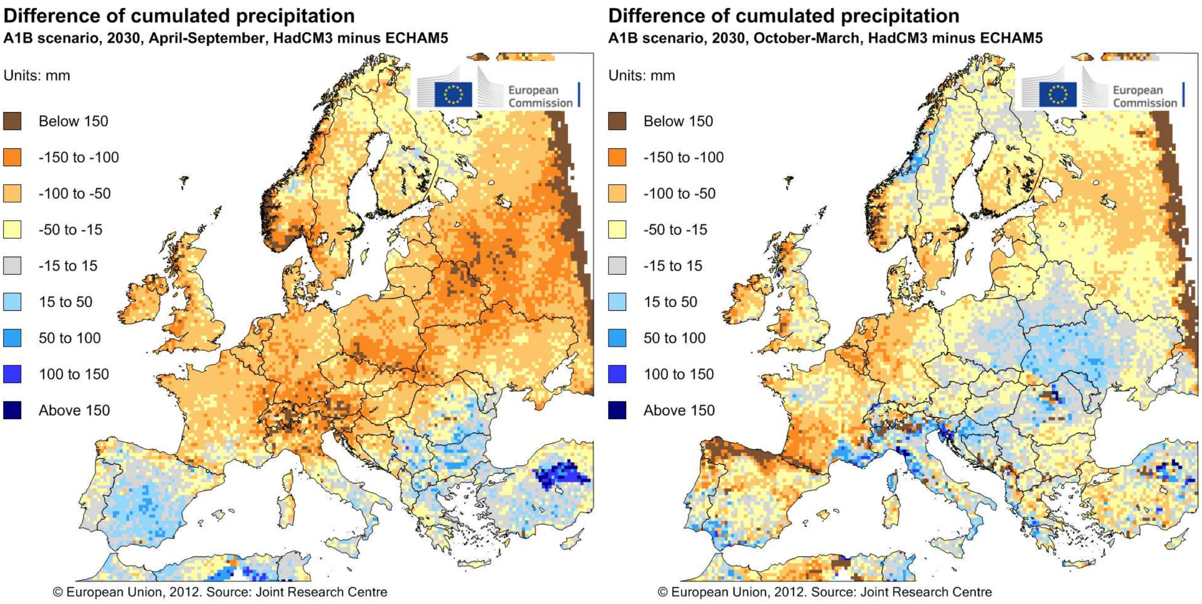


Figure 29. Difference of cumulated precipitation (HadCM3-ECHAM5, A1B, 2030) for April-September (left) and October-March (right)

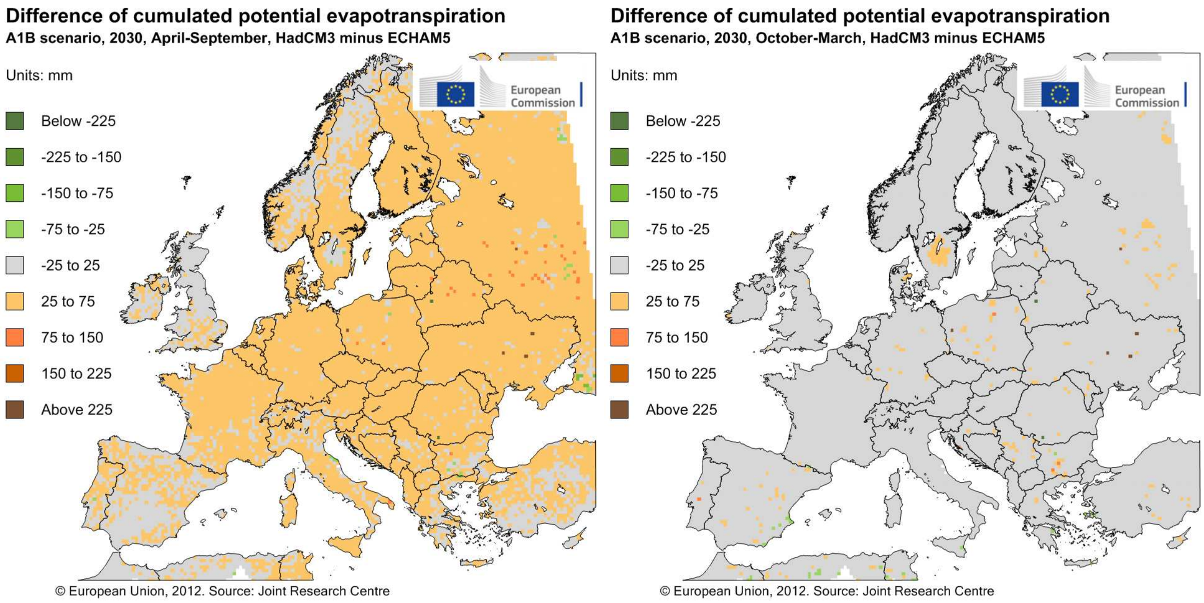


Figure 30. Difference of cumulated potential evapotranspiration (HadCM3-ECHAM5, A1B, 2030) for April-September (left) and October-March (right)

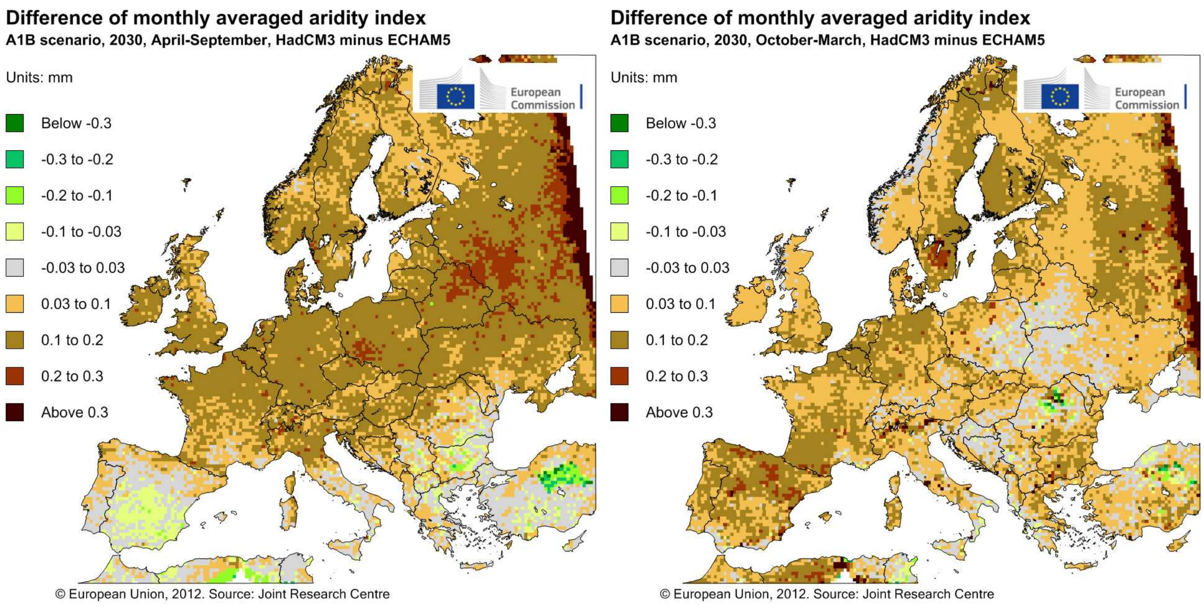


Figure 31. Difference of monthly average aridity index (HadCM3-ECHAM5, A1B, 2030) for April-September (left) and October-March (right)

3. Agricultural areas under general climate constraints

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3.1. Introduction

The method described in the chapter is closely linked to previous evaluations made for the EU territory of the various climatic factors influencing the agricultural conditions under the Less Favoured Area scheme, also known as Areas with Natural Handicaps.

The Less Favoured Areas (LFA) scheme has existed since 1975 and is a broad mechanism for improving the viability of agriculture in areas with natural handicaps. The common criteria of second LFA category Intermediate LFA (Art. 19) have been developed for the European Commission's Directorate-General for Agriculture and Rural Development to satisfy the objectives in the Rural Development Policy (Axis II), which aim to improve the environment and the countryside by more sustainable land management.

LFA can be defined using, among others, constraints defined from weather data hence so called area with climate constraints. A classification based on static generic indicators can be of use for estimating weather impact on multiple aspects, and, although not being specific to a crop, does not require the assumptions that an articulated simulation requires.

In this way, the same methodological consideration can be used for the current study under various climate change scenarios.

Estimates of the changes of the area with climate constraints can hence be seen as another layer of information to identify potential vulnerability of agricultural production in the EU27.

The objectives of this study were:

- Develop a methodology to upscale from grid level (25 km x 25 km) to NUT2 level;
- Estimate changes in the Area with climate constrains at NUT2 level using agro-meteorological indicators.

3.2. Method

Common climate, soil, and terrain criteria for classifying land according to its suitability for generic agricultural activity were developed by experts, coordinated by the European Commission’s Joint Research Centre. The criteria proposed covers temperature, heat stress, drainage, soil texture and stoniness, soil rooting depth, soil chemical properties, soil moisture balance and slope. If at least one criterion is flagged then area is considered as area with climate constrains. Four climate related criteria are already tested at European scale using daily weather data in 50 × 50 km^2 resolution provided by the EC JRC Monitoring Agriculture with Remote Sensing database (MARS, 2010). The criteria are currently being tested by the EU Member States at higher national scale for a future possible legislation. For assessing future climate change impacts on Area with climate constrains and agriculture in Europe, the “warm” and “cold” realization of the A1B emission scenario prepared as described in chapter 2 are used as inputs.

Maps were produced for each climate parameter for the years 2000, 2020 and 2030 in grid map shape and at NUTS2 level, in addition one aggregation map, which reflects dynamic change of Area with climate constrains area at NUTS2 level. The 66% threshold of affected area at NUTS2 level has been chosen because the consideration of utilized agricultural area (UAA) spatial dispersing in NUTS2 units. The anticipation of low-level spatial intersection of UAA area and Area with climate constrains affected area inside NUTS2 unit is considered. The latest proposal for legislation keeps 66% threshold as well.
The following constraints were analysed:

- **Length of Growing Period**. Length of Growing Period (number of days) defined by number of days with daily average temperature > 5°C (LGPt5). The threshold is ≤ 180 day.
- **Thermal-time Sum**. Thermal-time sum (degree-days) for Growing Period defined by accumulated daily average temperature > 5°C. The threshold is ≤ 1500 degree-days.
- **Heat Stress**. Number and length of continuous periods (number of days) within the growing period for which daily maximum temperature (Tmax) exceeds the threshold. The threshold is one or more periods of at least 10 consecutive days with daily Tmax > 35°C. If the probability of exceeding the threshold in an area is more than 20% (i.e. this constraint occurs at least in 3 years out of 10), then the area is considered to be severely affected by heat stress. This criterion in Europe is overlapped completely by Aridity Index criterion. This is the reason why the Heat Stress criterion has been removed from the proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) on 12 October 2011.
- **Aridity Index**. An aridity index (AI) is a numerical indicator of the degree of dryness of the climate at a given location. AI is index estimated by annual average precipitation divided by annual average potential evapotranspiration. An aridity index defined by the United Nations Environmental Programme (UNEP) and suggested by Pereira et al., 2009. The threshold of severe limit corresponds to AI UNEP values less than 0.5.

3.3.Appropriate figures

CHANGES IN “WARM” SCENARIO

Status 2000:

Area constrained is: Entire Finland, Sweden: Norra Mellansverige, Mellersta Norrland, Ovre Norrland, Stockholm, UK: Eastern Scotland, North Eastern Scotland, Highlands and Islands, Hungary: Kozep-Magyarorszag, Del-Dunantul, Del-Alfold, Czech Republic: Praha, Slovakia: Bratislavsky kraj, Greece: Anatoliki Makedonia, Thraki, Kentriki Makedonia, Dytiki Makedonia, Thessalia, Sterea Ellada, Peloponnisos, Atiki, Voreio Aigaio, Kriti, entire Bulgaria, Romania: Nord-Est, Sud-Est, Sud-Muntenia, Bucuresti-Ilfov, Sud-Vest Oltenia, Austria: Salzburg, Tirol, Italy: Valle d’Aosta, Bolzano, Puglia, Calabria, Sicilia, Sardegna, Spain: Aragon, Comunidad de Madrid, Castilla y Leon, Castilla-La Mancha, Extramadura, Comunidad Valenciana, Illes Balears, Andalucia, Region de Murcia, Portugal: Algarve, Lisboa, Alentejo.

2000-2020:

Norra Mellansverige (SE), Etela-Suomi (FI), Bratislavsky kraj (SK), Sud-Vest Oltenia (RO), Yugozapaden (BG), Del-Dunantul (HU) and Calabria (IT) leave the constrained area. There is no area joining the Area with climate constrains.

2000-2030:

Norra Mellansverige (SE), Ita-Suomi, Lansi-Suomi (FI), Sud-Vest Oltenia (RO), Del-Dunantul (HU) and all UK's affected area leave the constrained zone. Wielkopolskie (PL), La Rioja (ES), Molise (IT), Kozep-Dunantul, Eszak-Magyarorszag, Eszak-Alfold join the Area with climate constrains.

2020-2030:

Norra Mellansverige (SE), Etela-Suomi (FI), Del-Dunantul (HU) and all UK's affected area leave the constrained zone. Wielkopolskie (PL), Bratislavsky kraj (SK), La Rioja (ES), Molise, Calabria (IT), Kozep-Dunantul, Eszak-Magyarorszag, Eszak-Alfold (HU) join the Area with climate constrains.

CHANGES IN "COLD" SCENARIO

Status 2000:

Area constrained is: Entire Finland and Estonia, Sweden: Norra Mellansverige, Mellersta Norrland, Ovre Norrland, Ostra Mellansverige, Smaland med oarna UK: Eastern Scotland, North Eastern Scotland, Highlands and Islands, Northumberland and Tyne and Wear, Hungary: Kozep-Magyarorszag, Del-Dunantul, Del-Alfold, Greece: Anatoliki Makedonia, Thraki, Kentriki Makedonia, Thessalia, Sterea Ellada, Atiki, Voreio Aigaio, Kriti, Bulgaria: Severen tsentralen, Severoiztochen, Romania: Sud-Est, Bucuresti-Ilfov, Austria: Vorarberg, Salzburg, Tirol, Karnten, Italy: Valle d'Aosta, Bolzano, Puglia, Sicilia, Spain: Comunidad de Madrid, Castilla-La Mancha, Extramadura, Comunidad Valenciana, Illes Balears, Andalucia, Region de Murcia, Portugal: Algarve, Alentejo.

2000-2020:

Norra Mellansverige, Ostra Mellansverige, Stockholm (SE), Estonia, Yogoiztochen (BG), Kernten (AU) leave the constrained area. South Wetern Scotland (UK), Sud-Muntenia (RO), Aragon (ES) join the Area with climate constrains.

2000-2030:

Norra Mellansverige, Ostra Mellansverige, Stockholm (SE), Estonia, Vorarberg, Kernten (AU), Eastern Scotland, Northumberland and Tyne and Wear (UK) leave the constrained area. Nord-Est, Sud-Muntenia (RO), Aragon (ES), Lisboa (PT), Severozapaden, Yugoiztochen (BG), Sardinia (IT), Del-Alfold (HU), Dytiki Makedonia, Peloponnisos (GR) join the Area with climate constrains.

2020-2030:

South Western Scotland, Eastern Scotland, Northumberland and Tyne and Wear (UK), Vorarberg (AU) leave the constrained area. Del-Alfold (HU), Nord-Est (RO), Severozapaden, Yugoiztochen, Severoiztochen (BG), Sardinia (IT), Dytiki Makedonia, Peloponnisos (GR) join the Area with climate constrains.

3.4.Brief analysis

Warm scenario

Considering Areas with climate constraint in "warm" scenario we can see that Pyrenean and Apennine peninsulas are not significantly impacted. Big part of Northern Europe leaves areas with climate constraint zone basically because of mean annual temperature increase. We experience areas with climate constraint decrease in Balkans, due to an increase of precipitation. In 2030 we experience areas with climate constraint increase in Poland and Hungary because of arid continental climate influence coming from Russia and Ukraine.

Cold scenario

Northern Europe experiences a decrease of areas with climate constraint, but not as severe as in warm scenario. In the Mediterranean countries we see a slightly increase of areas with climate constraint zone. Balkans particularly experiences an area with climate constraint zone increase in 2030 mainly because of precipitation decrease.

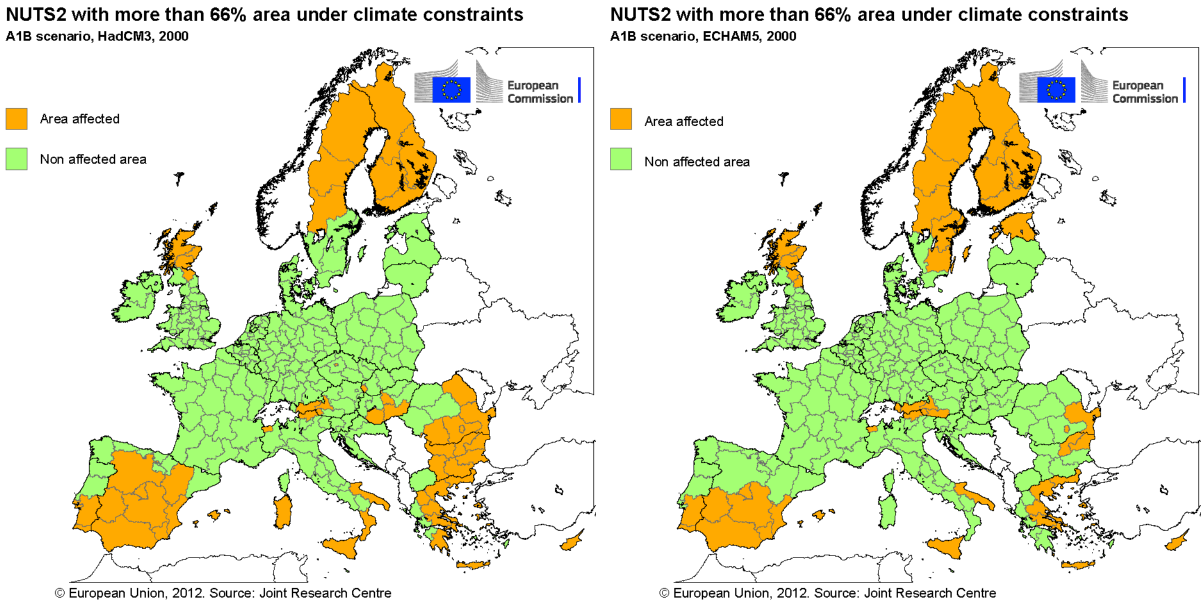

Figure 32. Regions with areas under climate constraints for the 2000 time horizon based on the warm HadCM3 (left) and cold ECHAM5 (right) A1B realizations.

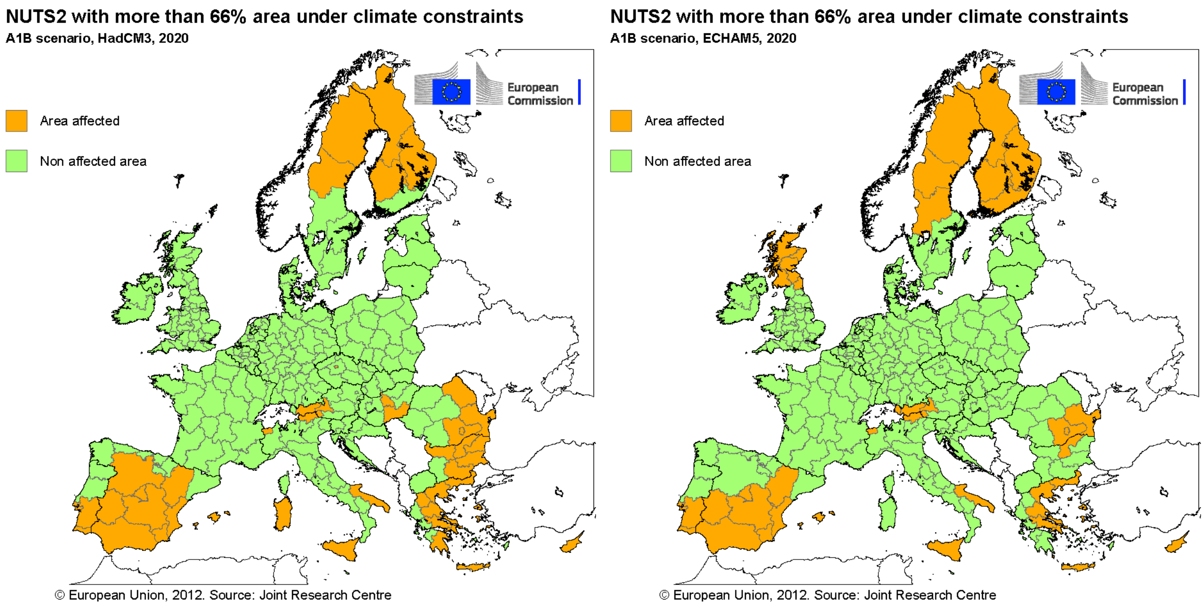

Figure 33. Regions with areas under climate constraints for the 2020 time horizon based on the warm HadCM3 (left) and cold ECHAM5 (right) A1B realizations.

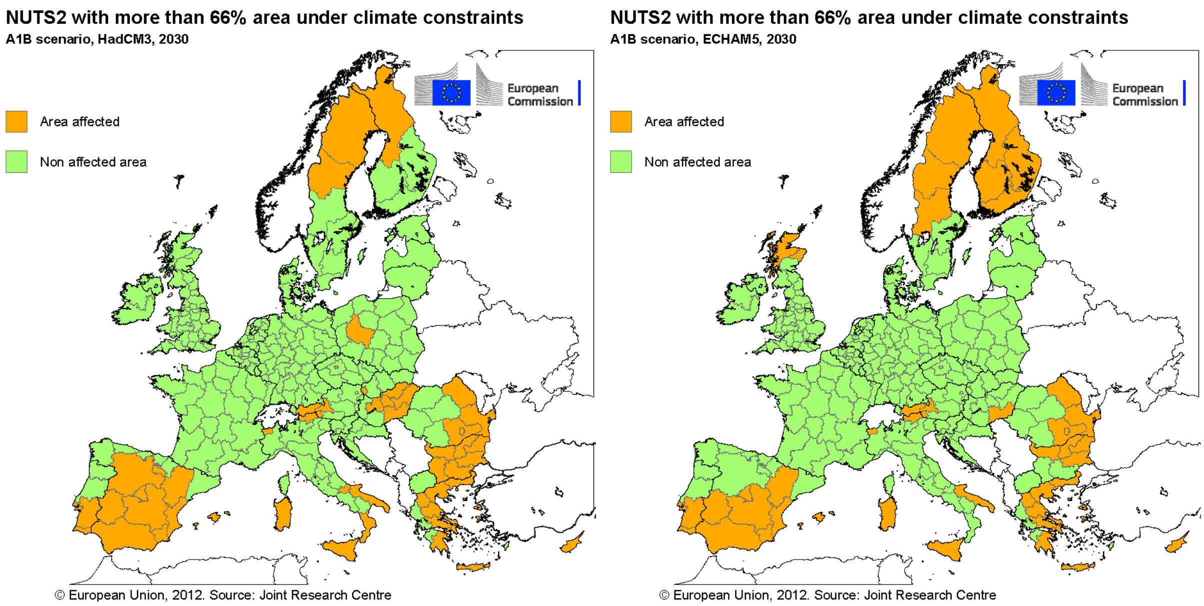

Figure 34. Regions with areas under climate constraints for the 2030 time horizon based on the warm HadCM3 (left) and cold ECHAM5 (right) A1B realizations.

4. Biophysical model simulations of priority crops

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4.1. Introduction

The impact of weather on a specific crop is ultimately given by the crop response at specific timings during its cycle. Each crop has its own range and pattern of temperature response. The crop biological processes respond often in a non-linear fashion, showing also non-linear responses of the interactions among them. As discussed by Donatelli and Confalonieri (2011) and detailed in the methodology of the analysis presented in this chapter, there is no analytical solution to the response of crops to the environment, and simulation models based on finite difference procedures are needed to explore scenarios in which no data has been previously collected. The analysis run has not explored technical adaptation of systems to the changed weather scenarios.

The objective of this work package is:

- To simulate priority crops over the EU27 member states to quantify the impact of climate change scenarios on current systems.

4.2. Description of the modelling/software platform

Modelling system

The models used in this study are process-based models, which allow for the simulation of crop-soil interactions affected by weather and agricultural management. The simulation tools to be used are implemented in the platform BioMA (Biophysical Model Applications), an extensible software platform for running biophysical models on generic spatial units. The guidelines followed during its development aimed at maximizing:

- Extensibility with new modelling solutions
- Ease of customization in new environments
- Ease of deployment

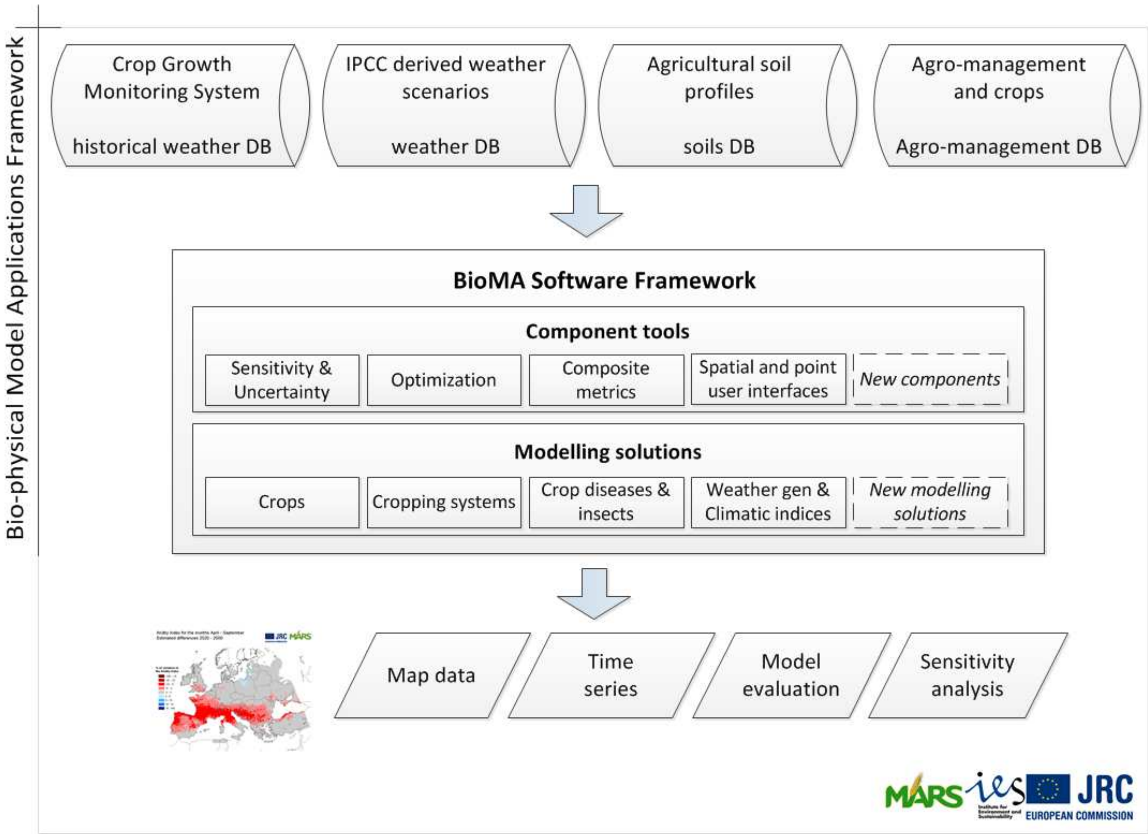


Figure 35. BioMA macro-components

Models available

The current version of BioMA includes diversified and alternate modelling solutions, as listed below. While crop model approaches available in the platform are known and well tested, new sub-models have been linked to estimate diseases and critical response of crops to extreme events:

- WARM-BlastDisease-Sterility (rice simulator)
- CropSyst-Water Limited (generic crop/cropping systems simulator)
- WOFOST-Water Limited (generic crop simulator)
- APES (cropping system simulator)
- Potential infection due to plant diseases
- Diseases (linked to crops: environment potential, epidemiology, crop damage, agro-management)
- ClimGen (Weather generator)

Sensitivity and uncertainty analysis

All BioMA modelling solutions can be run to perform a sensitivity analysis with the existing tools within BioMA (see Figure 35). The deterministic models used in this project are run in a stochastic fashion using samples of weather and two GCM models. Probability distributions and, more in general, metrics of variability, are consequently produced allowing the estimate of results uncertainty with respect to weather variability and GCM.

4.3.Methodology used to produce the biophysical simulations of the target crops

Impact assessment of climate scenarios on agriculture requires a very large simulation experiment. This experiment is done using the biophysical models within the BioMA platform. The design of this experiment aims at prioritizing basic responses of crops and, in a possible future continuation using these results, of cropping systems.

An in-depth analysis of even a single crop in a specific region would require a much greater level of detail (as inputs and simulation runs) of what is achievable in this project. However, the infrastructure allows extending the database to target areas with a much higher spatial resolution.

Setting up the experiment for AVEMAC involves calibrating the models for the target crops and also making choices on the static and dynamic layers of input data necessary to run the simulations. Particular emphasis is placed on having adequate weather data for the future climate scenarios, since this is the main driver of simulations results. Special attention is required to the evaluation of the crop models along with the limitations and assumptions that are made in this experiment. All of these points are described in detail in the following subsections.

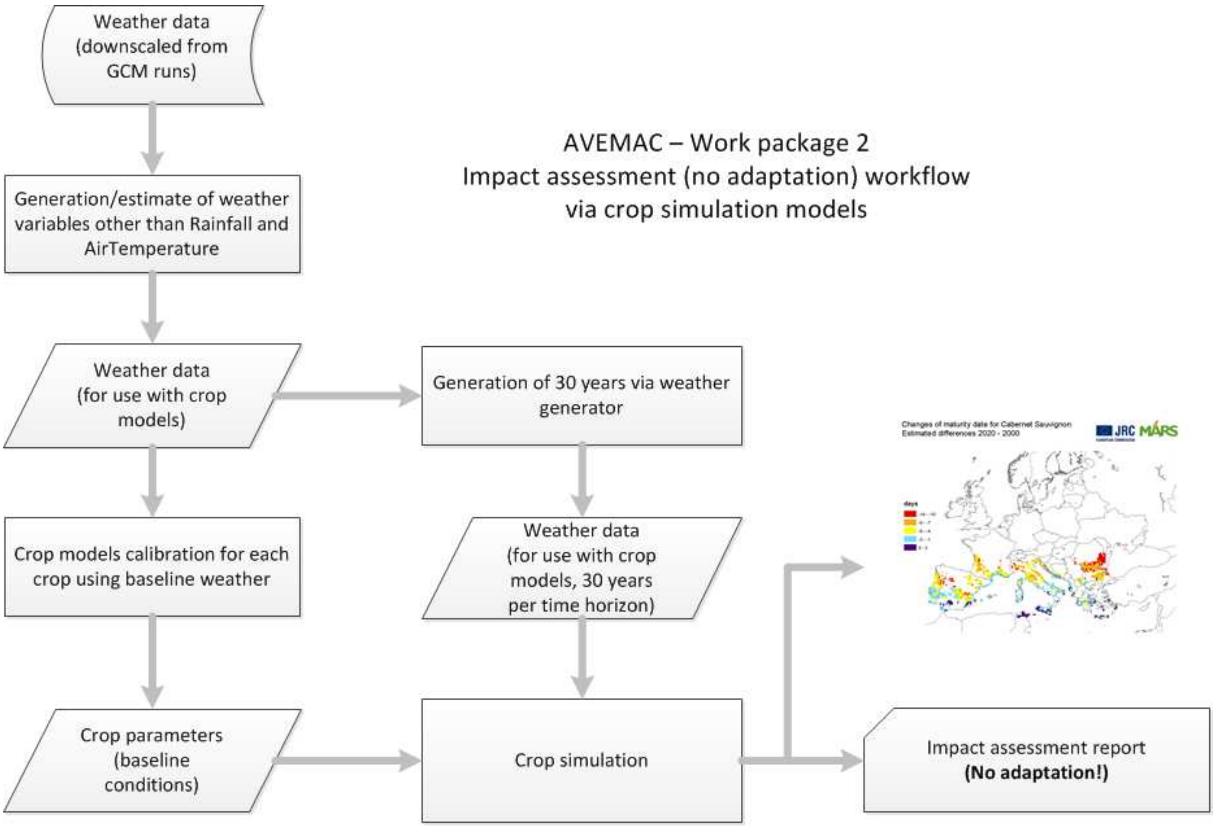


Figure 36. Workflow for crop simulations

Static data

Simulation grid

Simulations are run on a 25 x 25 km^2 grid that covers Europe in the Lambert Azimuthal Equal Area projection. This grid is the same as the one used operationally to forecast yields within the growing season by the MARS Crop Yield Forecasting System (MCYFS).

Time horizons

The time horizons studied in AVEMAC are 2020 and 2030, which are to be compared to a baseline representing conditions in 2000. This contrasts with the majority of climate change impact studies that generally target a time horizon of 2050 or 2100, for which a contrast with a baseline might be stronger (but for which the projections of the climate are more uncertain, among other factors).

Soils

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 the most common soil profile available in the database is used for all cells and for all the simulation runs. This soil has a medium water-holding capacity.
It must be pointed out that the simulations limited to soil water are sensitive to basic soil parameters derived from texture, and soil depth, as they determine the hydraulic characteristics. In other terms, while a more detailed database that would better represent actual soil depths and % of presence in a given cell could improve the representativeness of simulations for that cell, the differences in the output would not differ markedly except for extremely shallow soils.

CO_2 concentration

The average CO_2 concentration in the atmosphere needs to be defined for each future time horizon that is studied. This concentration has been set to 355 ppm for the 2000 (the baseline), 400 ppm for 2020 and 420 ppm for 2030, in coherence with IPCC assumptions.

Crop simulation

Crop simulations for each crop and each climate change scenarios were performed and compared to the baseline results. Such simulation sets were made targeting, as objective of this project, no adaptation from farmers, i.e., same cultivars and agro-management used under current conditions.

Clearly, the first set of simulation results is in practice rather pessimistic, given that farmers' responses to modified weather conditions are to be expected. Nonetheless, the first “no adaptation” set of results serves as a key benchmark, against which to measure in the future the benefits of realized adaptation actions.

The general definition of adaptation is given by changes in agricultural management that farmers may implement to alleviate negative impacts of the weather scenarios evaluated. Adaptation by farmers will occur, to some extent, regardless of any action to support or steer it from government or local authorities. Consequently, although simulating impact assessment for "unchanged systems" is a prerequisite to get insights of system behaviour with the target of developing adaptation strategies, its results should not be consider as one of the possible "future scenarios for agriculture".

Water supply was always active in simulations for irrigated/potentially irrigated crops (maize in this study), while all combinations related to genotype and planting time were explored. Crops were simulated in cells where their relative occupancy resulted 1% or greater of the agricultural area. The modelling capabilities of the platform allow simulating, for each crop, adaptation strategies, weather scenarios, and different abstractions of production systems identified as production levels:

- Potential production (P: crop growth solar radiation and temperature driven);

- Water limited (WL: all factors of P and water limitation);
- Abiotic stresses limited (AL: P and effects due to temperature stresses of extreme events for crops);
- Disease limited (DL: P and impact from one crop-specific disease);
- Multiple factors limited (MFL: P, WL, AL, and DL limited).

The simulation of potential production, as defined above, is useful to test responses not constrained by either resources - as quantities, or technology (or both). Consequently, estimating a multiple factors limited production allows estimating the technological gap (e.g. we do not use a pivot system to irrigate weekly, hence no more than four irrigation events per season via sprinkler) and resource limited production (e.g. no more than 300 mm /season of water available). Noticeably, the levels potential production and abiotic stress limited production can be counteracted as adaptation measures either via planting different genotypes and changing timing of sowing (same crop), or changing crops.

When water limited production was simulated, a rule-based agro-management model to supply water to crops was used i.e. adaptation with respect to water use was included for maize only (adaptation not constrained by water availability beyond the setting of rules, and not constrained by technology). The picture provided by WL simulations estimates a possible technical adaptation, whereas context specific constraints (e.g. no more than 150 mm/season of irrigation; no more than three irrigations) can either be considered ex-post evaluating the adaptation scenarios provided, or may lead to another run of simulations. Note that the simulation with automatic irrigation via the WL management rules on maize accounts for totally rain-fed crops; in fact, irrigation triggers only in very strong stress conditions, which do not occur in areas in which the crop is not irrigated. All other crops (wheat, rapeseed, sunflower) were simulated as exclusively rain-fed, whereas water limitation is not considered for rice, which is grown as paddy rice.

The simulation of diseases limited production does not include agro-management to alleviate the impact of a possible increased pressure by plant pathogens due to climate change. One pathogen per crop, as judged as the most important for the crop, was simulated. These simulations can be of direct use if no chemical can be used in a given context; otherwise simulation results would overestimate the impact of climate change neglecting possible adaptation (see opening paragraph). In the latter case, economists could use the quantitative estimates of diseases-limited production could be used in a semi-qualitative fashion. In other words, disease limited yield is potential impact of diseases on a crop. From the above, the assumption made using scenarios of water-limited production is that diseases, if affecting the crop, will be either chemically or genetically controlled.

The choices of production systems in this project focus on the basic food commodities-based production systems abstracted at the level of “crops”. However, it must be pointed out that the simulation of impacts considering the system crop-disease is completely innovative. Also, the platform is suitable for more detailed analysis as scale and/or context specificity. Besides the meaning of simulation with no adaptation, which should be considered with extreme caution, it must be pointed out that agricultural management inputs for simulations, specifically planting dates and varieties, are abstracted at the level of grid (25 x 25 km^2), hence summarizing a range of possible production systems and contexts, the latter given for example by soil characteristics and slope.

The final report includes potential production, water limited estimates, and disease limited estimates. The abiotic stresses limited simulations are not presented because the adequacy of the modelling is different for different species, being for instance well developed for rice and totally absent for rapeseed. Consequently, presenting this level of production would have introduced a bias in the inter-crop comparison. The multiple factors limited yield simulations are not presented because they would include not only the abiotic stresses as above, but also the diseases-limited production as discussed above, producing a picture far worse than real systems, where diseases are sufficiently controlled to ensure production on crops and in environments where needed.

Calibration

Process-based, deterministic models like the ones used for simulation in this project, are evaluated against referenced data. This activity, often referred as model "validation", for crop/cropping system models is done by simulating the same conditions where the reference data were collected (weather, soil, agricultural management) and comparing simulation results to data collected from the real system (e.g. biomass produced, yield, soil water content). Prior to actually performing model evaluation the model is calibrated, a process that comprises adjusting the value of model parameters in order to minimize the difference between simulated and reference data. This is a very delicate process when performed with process based models, where parameters have a bio-physical meaning; in no case the result of calibration must lead to parameter values out of the range known for the process they refer to. Once model parameters are calibrated, model evaluation is run as described above against an independent dataset. This is the calibration work shown in lower left of the workflow diagram in Figure 36.

Crop model evaluation

In all cases, model evaluation is run against articulated dataset, in which not only the context is described in detail to allow simulating it, but also the measurements on the state of system regard both different variables and time series. In fact, yield, which is very often the variable of major interest, is the final result of the simulation of several processes. As such, (dataset always being limited in number because very costly), a calibration based only on yield has often multiple solutions, often resulting in unpredictable model performance under changing bio-physical contexts. Model outputs such as crop progression through different development stages (phenology) is typically driven by a much smaller number of factors than yield. Models are simplified representations of the real system, and they must include the essential processes (as sources of variability of responses) with respect to the goal of the analysis planned. Some processes can be omitted, in this case adding to the assumptions made for the simulation exercise. Although acceptable, this has implication also on the data which can be used for model calibration and evaluation: for instance, if a model not simulating water limitation is used, reference data based on systems where water limitation occurs cannot properly be used either for calibration or evaluation.

The implications on which dataset can be used for evaluating a crop/cropping system model are important. In fact, whether models tend to simulate crop development and growth as limited by few factors, actual agricultural production systems, especially in developing countries, show a wide range of production constraints that may impact on production non-linearly. Unfortunately, yield statistics are presented as values, rather than ranges; should ranges be available, the upper limit could be used for calibration and model evaluation, allowing deletion from reference data of cases that cannot be represented by models, because they include processes, or technical mismanagement, which increase the yield gap. Furthermore, the technological gap of production system can be different across regions and countries; when combined to environmental factors; it may lead to a different resiliency with respect to adverse weather. The impact is again on the usability of yield statistics to calibrate and/or evaluate process based models, because it introduces a further bias as result of the year-by-year variability.

The models used in this project are well known and peer reviewed, which implies that they have been evaluated across a broad range of environmental conditions. The analyses carried out in this project thus are based on such evaluation, and rely on data from the scientific literature for model calibration. It must be pointed out that this study uses crop production as a level of abstraction for production system, hence aiming at representing yield changes (at various production levels) in response to scenarios via a 25 x 25 km^2 grid. Even if yields are considered at the various production levels mentioned above, yield estimates are potential, and can have different realizations in specific production system if analysed within more specific context constraints. This suggests that this type of analysis, using the very same tools, which allow for different spatial resolutions, could benefit from a more detailed calibration in specific countries or regions. Yet this level of detail in the analysis was beyond this project goals and resources; future applications involving local knowledge and expertise will be necessary to refine simulation results.

A different aspect of model evaluation to be considered relates to model use in scenarios of climate change. This refers to unexplored conditions where there is no data, site specific, which may represent the performance of production system. Being relationships among biophysical processes in the real system non-linear, system performance cannot be estimated using trends and statistical models. Likewise, it cannot be used by relying on empirical parameters whose empiricism is at the same level of the one of the estimate. The relationships used in process-based models also have some empiricism, but that empiricism will be one or more levels below the level of the prediction, as shown in Figure 37 below.

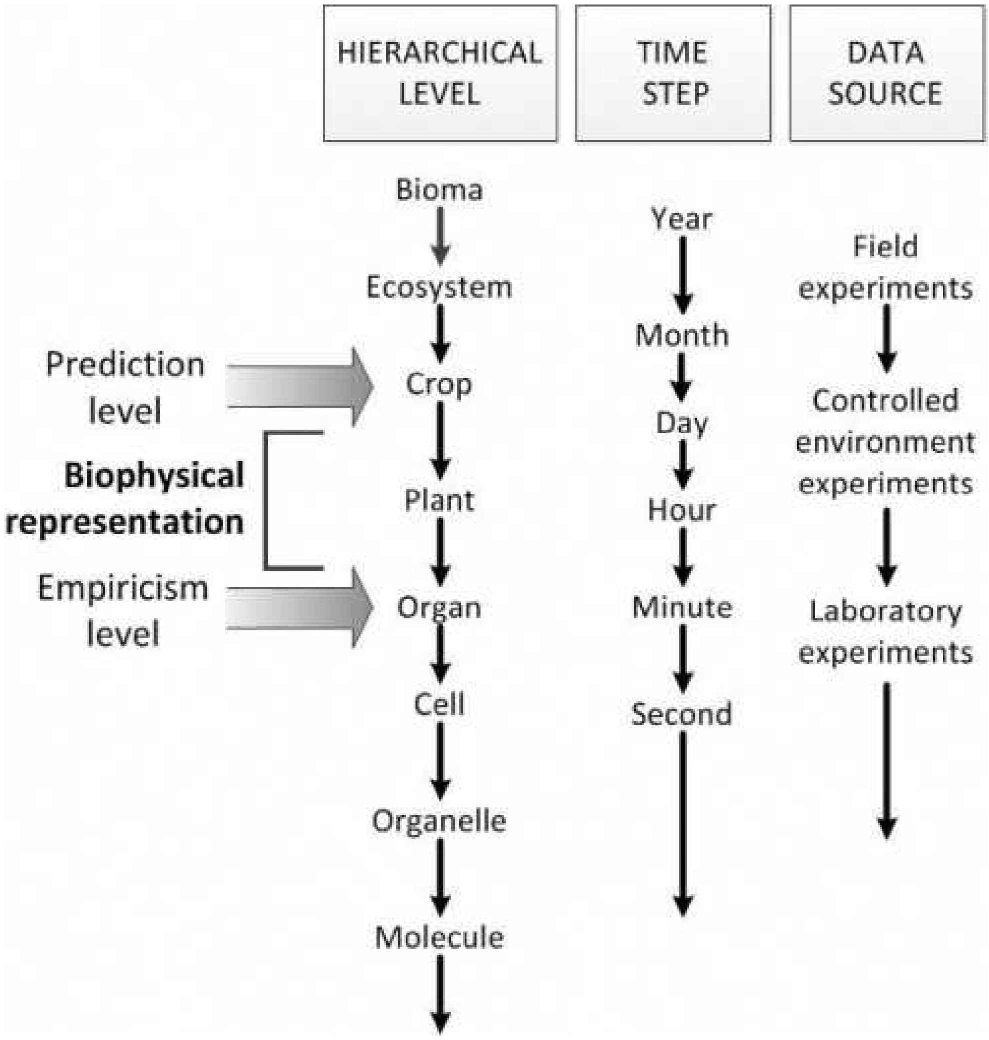


Figure 37. Level of prediction and level of empiricism in process-based models (redrawn from Acock and Acock, (1991).

The goals in defining new models are using relationships known from physics or chemistry, and parameters that have either a biological or a physical meaning. A process-based model can, in principle, be used to extrapolate to conditions outside the ones used to develop it. By contrast, a fully empirical model, as any statistical model, can be considered usable only for the context that originated the data used to build it.

Given that no evaluation against data can be done for scenarios of climate change impacting on crop development and growth, to accept their use in such condition a system analysis must be done confirming model adequacy under the new conditions. This has been done for the models used in this project, leading to changes in curves of response to temperature. The original models had a plateau of response to daily maximum air temperature, perfectly adequate in conditions such as the one of temperate climates, in which temperature rarely reaches levels above the optimum. Hence making the plateau approximation is acceptable. It is however known that rates of development and growth start decreasing above optimum temperature. For instance, a plateau model will estimate an overall increase of temperature-driven rates in the linear part of the response, and same response in the plateau region, when temperature increases as in climate change scenarios. By contrast, a curvilinear model will estimate a decrease of rates of development and growth at higher temperatures. The latter is the case in scenarios of climate change where the steep raise of temperature does not allow for accepting the hypothesis of good adaptation of crops to environmental conditions, as built in decades of agriculture under variable weather, but under no steep trend toward higher temperature. This is why the models used include curvilinear responses to temperature, which do not show any difference of estimates, compared to the original ones, under current weather, but start estimating differences at higher temperatures.

Another aspect that impacts on the adequacy of model structure, if the assumption of crop adaptation cannot be accepted, is the response to extreme meteorological events. We can consider that extreme events provide values of environmental variables for a crop that are beyond the capability of providing a physiological response by the crop, and which may lead either to a permanent damage or to death of the crop. Referring to air temperature as discussed above, a crop will respond with a given rate to temperature, but if temperature reaches levels beyond maximum temperature for growth, or below minimum temperature for growth, permanent damages occur. These aspects were generally ignored in commonly used modelling solutions, and are now implemented representing one of the production levels simulated.

Limitations and assumptions

Model calibration

Model calibration, was based on literature resources, which generally make available reference data for large areas. This means that this exercise needs to be significantly refined by interaction with local experts and stakeholders, so that the right cultivars and perhaps cropping systems could be simulated as opposed to the idealized types simulated herein. For this reason, although the general impact trends that were computed can be considered robust in terms of extensive regional signals across all four crop types simulated, specific crop-country results need to be interpreted with caution, since they are highly dependent on specific cultivars used in this round of simulations. As for weather data, an analysis at finer spatial scale is needed using local expertise would yield more articulate results per target areas.

Soils

As assumed for weather data, soils were distributed on a flat surface, i.e., terrain. This may alter significantly 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.

Effects of elevated CO_2

The effects of elevated CO_2 on crop growth and yield included in the BioMA platform are consistent with current findings (i.e., see Tubiello et al., 2008). Nonetheless, it is widely expected that CO_2 response in farmers' fields will be lower than found experimentally, so that the functions implemented in the simulations of this report are likely to represent an overestimate of actual field responses. 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 plant efficiency for C3 plants of up to 10%.

Production systems

Production systems were abstracted at the level of "crop", ignoring possible structures typologies of cropping systems. If cropping systems were analyzed instead, crop performance in a given cell would result from its performance in different rotations and under different inputs of resources. Also as a consequence of weather data resolution, model calibration, and soils, simulation results were an abstraction of production systems for the area, and should be compared to actual, point data, with caution. However, the goal of the analysis aims at estimating basic impact dynamics and adaptation strategies for the large areas considered.

4.4. Crop simulation results

The simulation results are presented as difference maps, ruling out the uncertainty associated to absolute values of estimates under the assumption of adequate modelling (model engine and calibration) in the weather scenarios analysed.

The levels of production presented are discussed in the crop simulation section.

The maps of yield gap show the difference between the potential and water limited levels of production estimated. These maps show the expected North-South gradients, and assist in interpreting the differences between potential and water limited yield across time horizon difference maps.

A series of maps present the coefficient of variation of the yields, which is calculated as:

$$c_v = \frac{\sigma}{\mu}$$

where σ is the standard deviation and μ is the mean of the yields over the period of time considered. The difference in coefficient of variation of yields between a time horizon and the baseline gives an indication if the resulting yields are more variable in the future period with respect to the baseline.

A general comment valid mostly for C3 species in these simulations (wheat, sunflower, rapeseed, rice) but valid to some extent also for C4 (maize), is that the latest projected levels of CO_2 for 2030 are much higher than the ones envisaged only a few years ago. Consequently, the positive effect of air carbon fertilization on plants starts being a factor even in the short term, projecting a gain in efficiency of about 10% already in 2030.

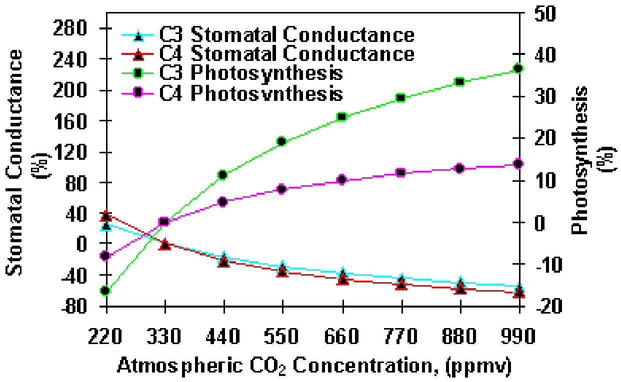


Figure 38. Photosynthetic efficiency gain for C3 and C4 species as a function of air CO_2 concentration as implemented in the CropSyst modelling approach.

Although the two realizations of the emission scenario A1B differ for estimates of air temperature, the difference is not large in view of crop responses. Instead, differences in rainfall can be substantial and are they key to compare results due to the different realizations of the emission scenarios in Southern Europe.

Estimates of disease limited production, although presented as differences, must be evaluated with caution and seen as preliminary trends. In fact, the analysis joining crop models to diseases models is still under evaluation, hence the results presented **must be considered as exploratory**. The diseases limited production level (and all other production levels) is described in the crop simulation methodology.

The results presented **do not include adaptation by farmers**. Whether the estimates can be considered as possible views on the future when yield is projected as improving, they overestimate the impact of future weather scenarios in areas where the impact assessment is negative (some endogenous adaptation would occur in any case).

HadCM3 realization of the A1B SRES ("warm A1B")

Wheat

Potential yield

Wheat phenology is anticipated due to the increase of temperature, which rarely hits above optimal temperatures, and is hence lower than maximum development rates. The impact on yield is more substantial at locations where both the increase of temperature is among the highest, and in a sort of belt of northern latitudes where a substantial part of development is centred on summer (at southern latitudes only the last part of grain filling hits the warmest period of the year). The situation changes in 2030 because of the further increase of temperature, which shortens more the grain filling period at Northern latitudes, but also start impacting at southern latitudes.

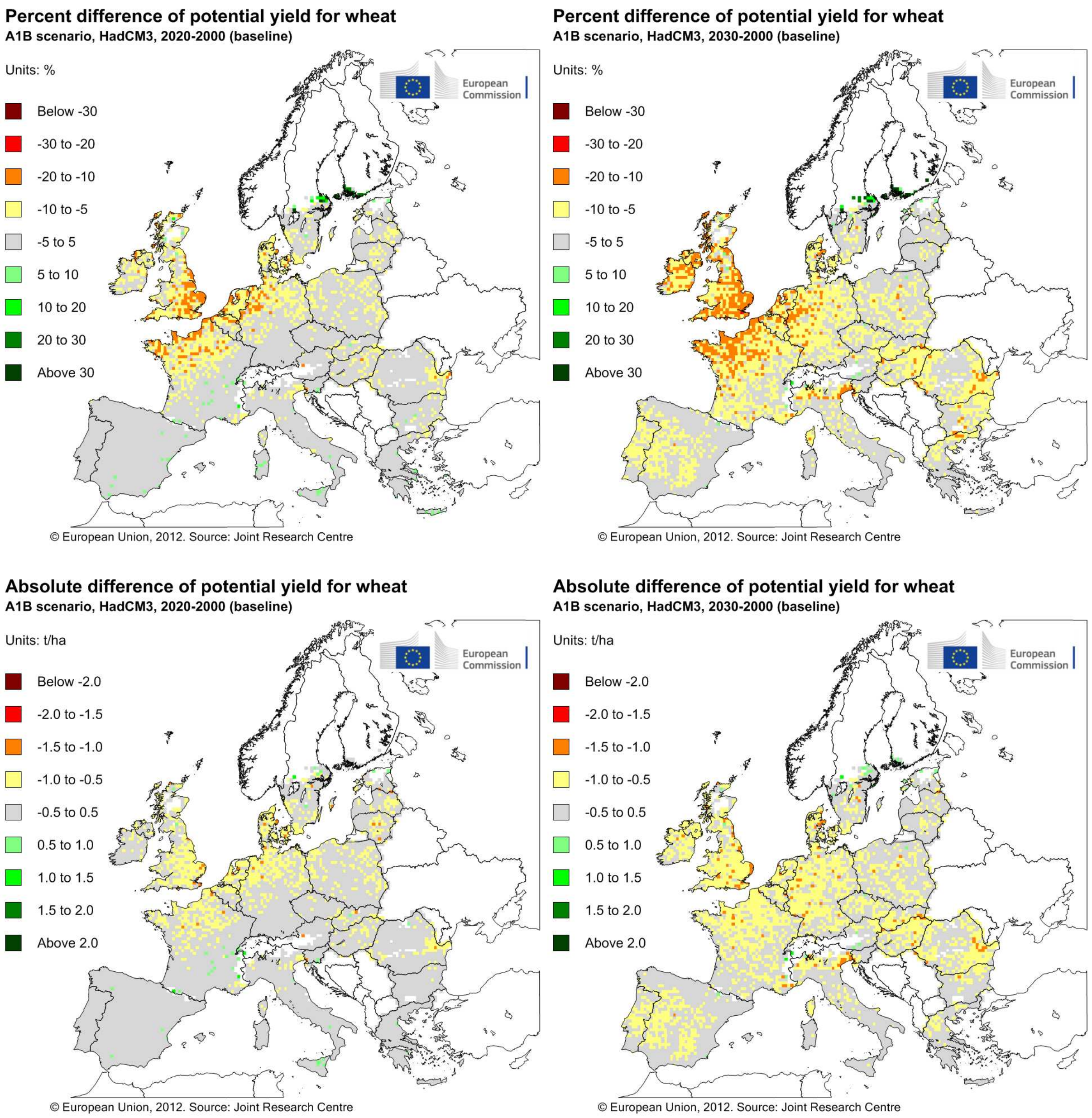


Figure 39. Change, in relative (top row) and absolute terms (bottom row), of simulated potential wheat yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

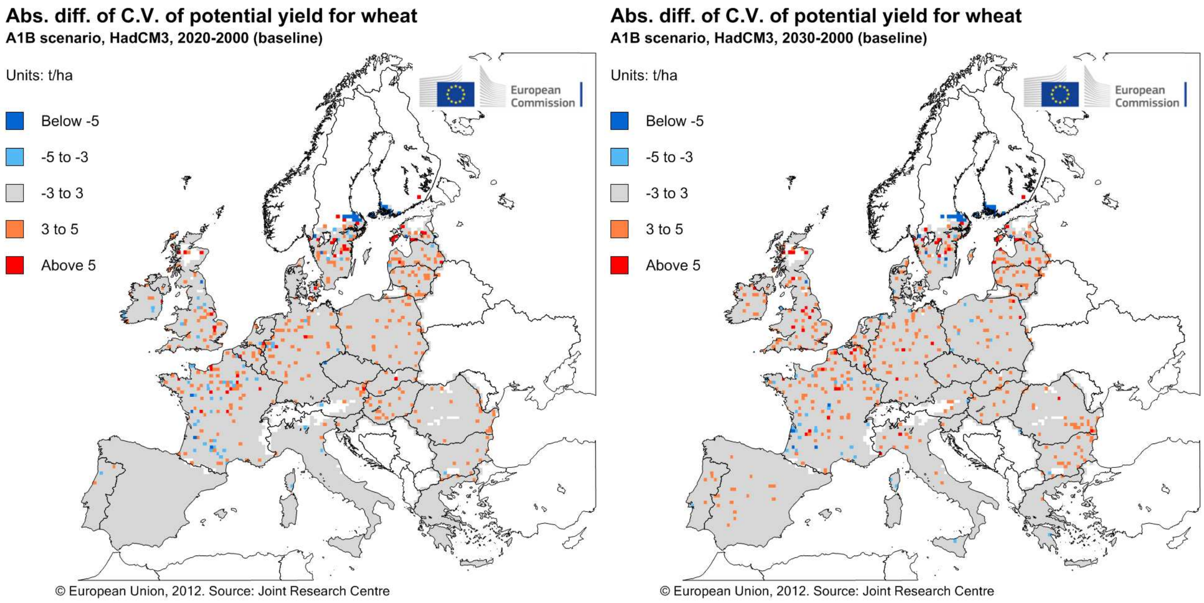


Figure 40. Change in the coefficient of variation of simulated potential wheat yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

The change of yield variability is spurious, being the combination of the maps of variability within time horizon, which do not change appreciably.

Water-limited yield

The evaluation of simulation results for water limited yields should start from the maps of yield gaps. Southern and Eastern Europe show a much higher yield gap, being North-West Europe much closer to potential productivity. This already suggests that increases in precipitation may cause a noticeable yield increase. In these cases, the shortening of the cycle may impact positively by improving the avoidance to summer water stress; even if a shortening of grain filling and of the cycle impacts on production, the yield map shows production system far from their potential. 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). Two other positive factors impact on simulation at Southern latitudes: the already mentioned CO_2 concentration, and the increase of rainfall. The overall result is a general pattern of improvement for water limited production in Southern Europe. Modest increases of yield correspond to these variations expressed as percentages (refer to yield gap maps) as shown in the maps of absolute differences. The picture is different in terms of direction for Poland, Germany, and in general Northern Europe, however, being the estimated decrease at most within 1.5 t/ha as average. The maps of the coefficient of variation do not present a clear pattern, with many areas unchanged, and the areas where rainfall is estimated as increased in the scenarios with a reduced variability compared to the baseline.

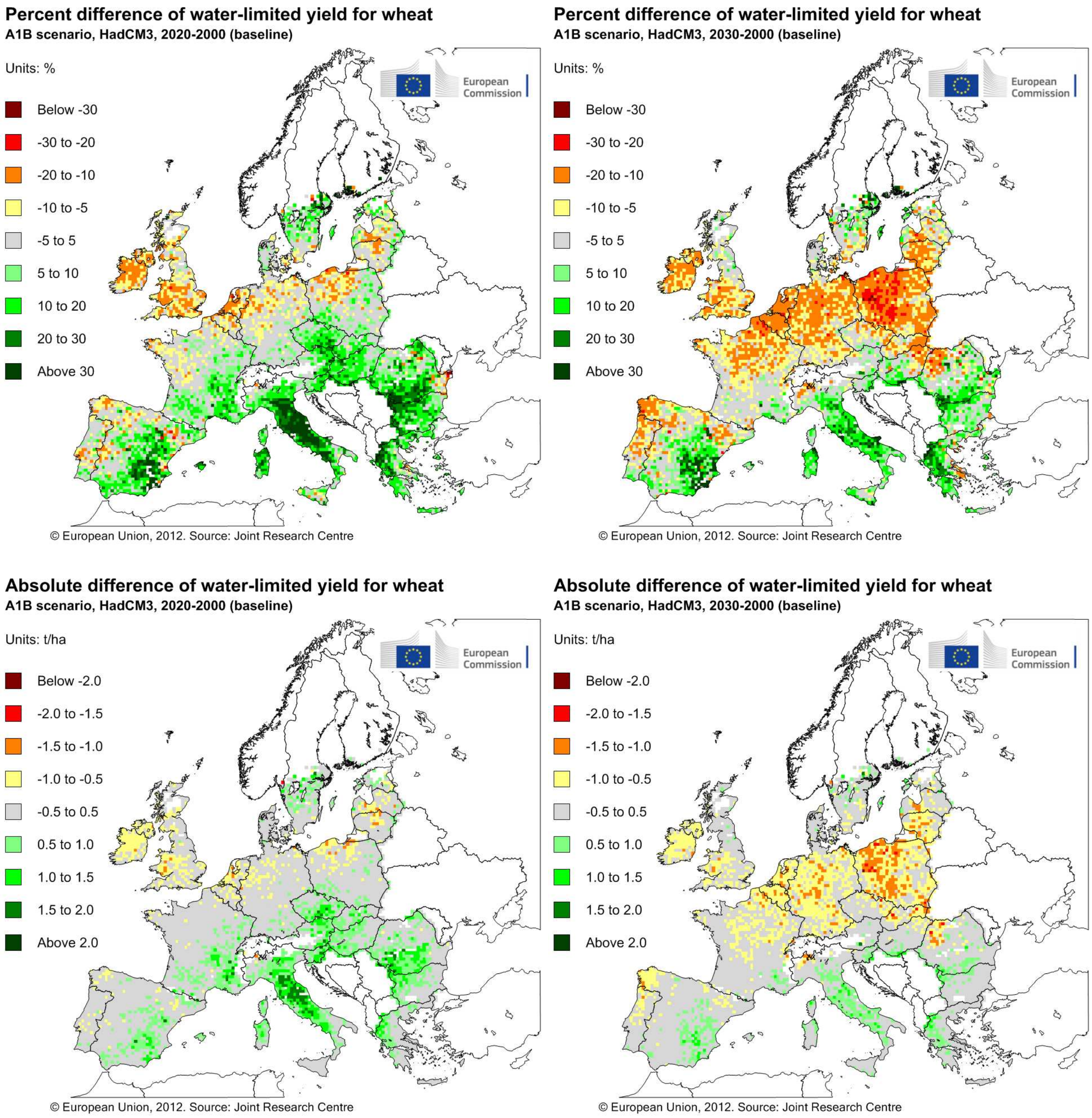


Figure 41. Change, in relative (top row) and absolute terms (bottom row), of simulated water-limited wheat yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

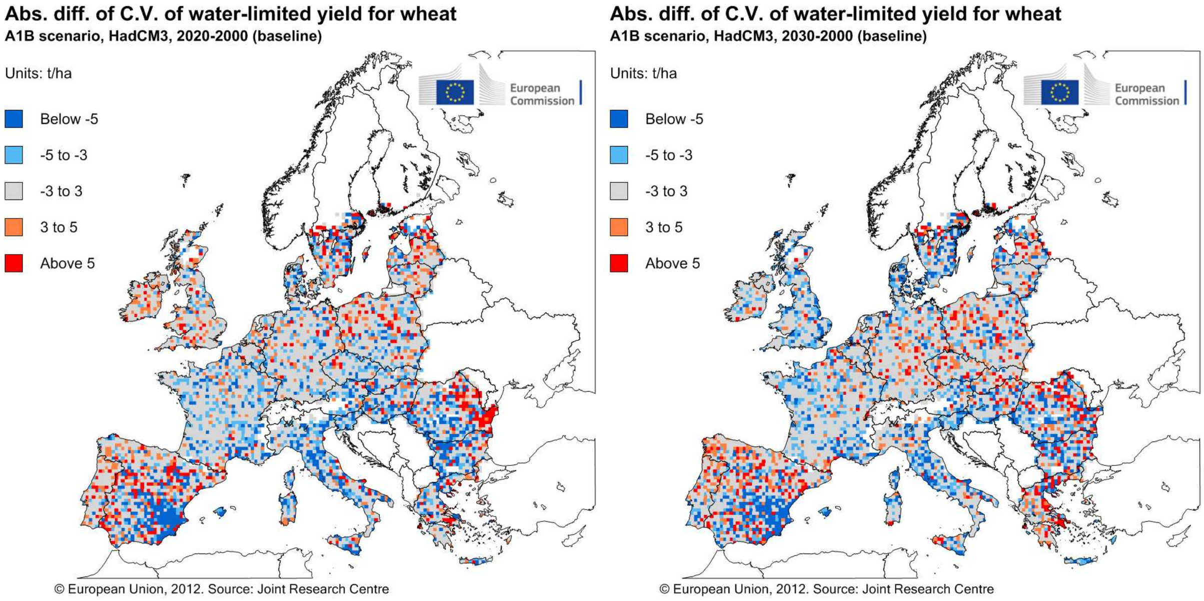


Figure 42. Change in the coefficient of variation of simulated water-limited wheat yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Yield gaps (potential – water-limited)

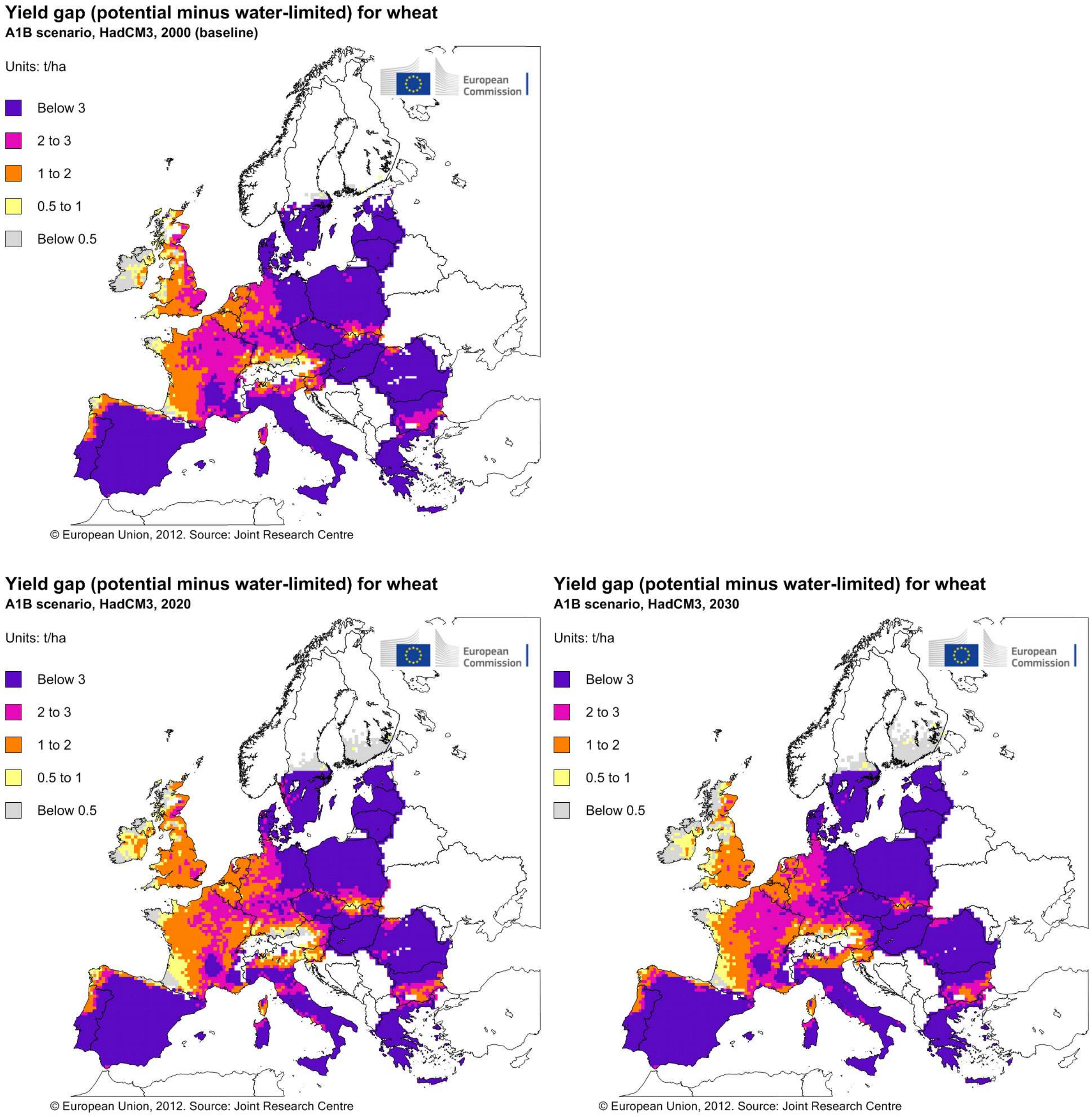


Figure 43. Wheat yield gaps, defined as potential minus water-limited simulated yields, for different time horizons, 2000 (top), 2020 (bottom left) and 2030 (bottom right), using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Disease-limited yield

The increase of temperature creates a more favourable environment for wheat leaf rust in Northern Europe, whereas it has no such impact in Southern Europe.

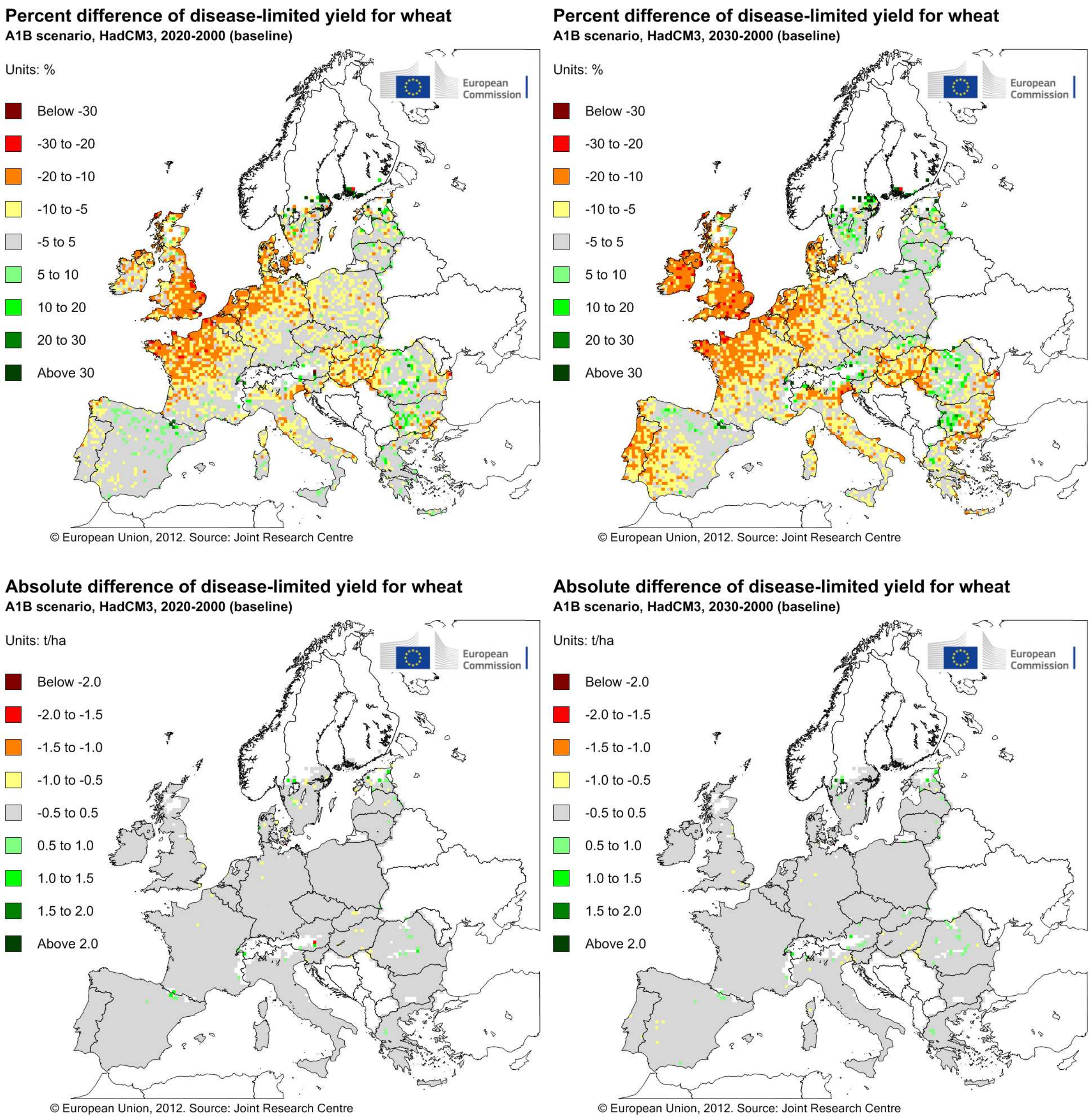


Figure 44. Change, in relative (top row) and absolute terms (bottom row), of simulated wheat yield limited by disease (*Puccinia recondita*) for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Maize

Maize is the only C4 species among the ones simulated, hence not responding as much as other crops to CO_2 concentration. Also, maize is the only crop, among the ones simulated (with exception of rice, which is in any case paddy rice) which has its growth cycle centred on summer.

Potential yield

Simulation results indicate improvements in maize yield especially in UK and Northern France by 5-10% whereas central and Southern part of Spain, Portugal and Bulgaria suffer a decline of 5-10% under potential conditions in the 2020 time horizon. Most of Europe remains unaffected. The effect of climate change is exacerbated in terms of yield decline mainly in Southern part of Europe.

However, significant gain in maize yield is foreseen in the Northern Europe in the 2030 time horizon.
Simulations indicate an anticipation of the maturity date for maize for most of Europe on the 2020 horizon that is more evident by 2030. Regions with a change within 5-10% in 2020 include Portugal, Spain, France, Germany and Poland but by 2030 a shortening of the cycle is visible even in Italy, Greece, Romania and Bulgaria.

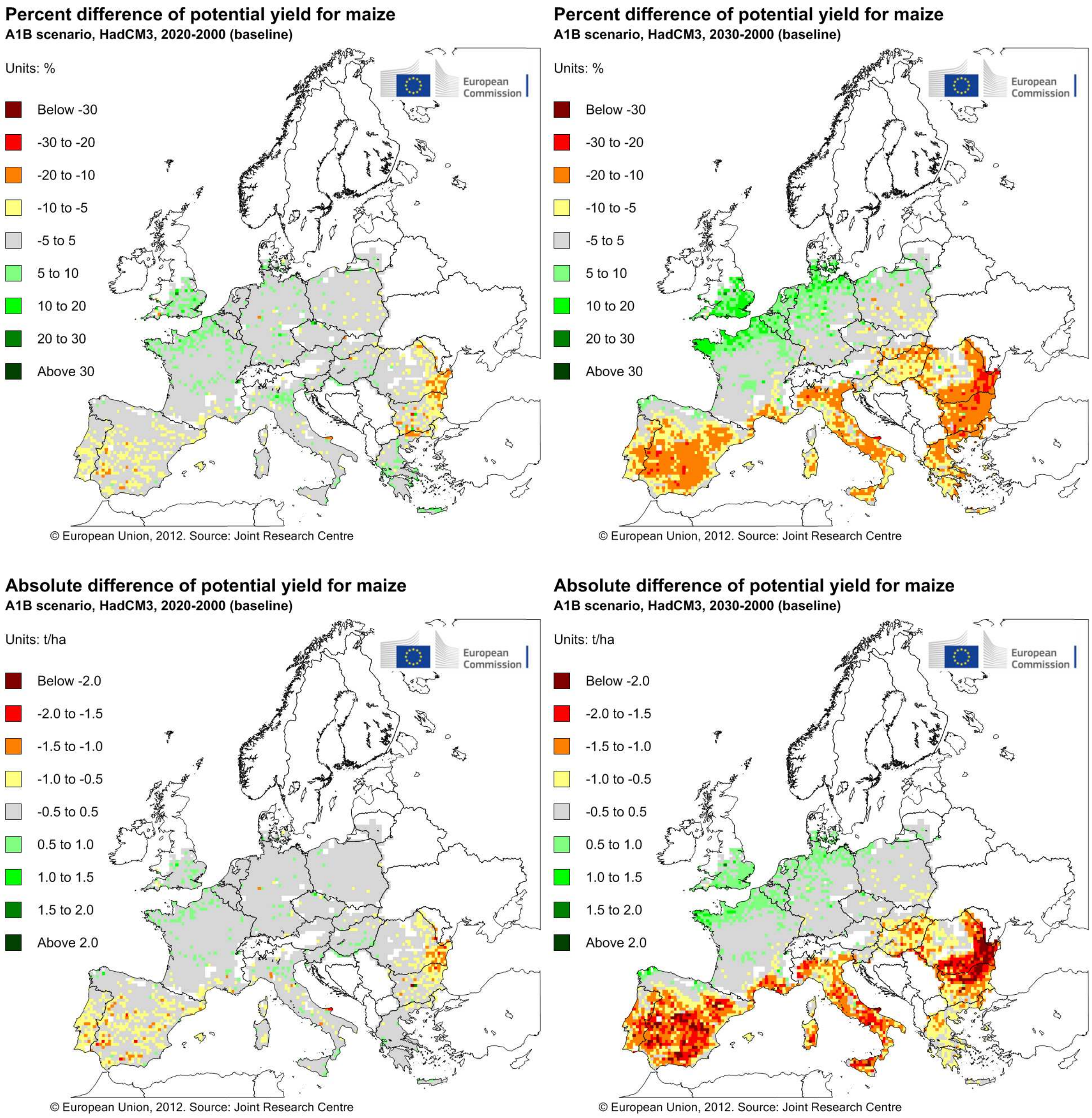


Figure 45. Change, in relative (top row) and absolute terms (bottom row), of simulated potential maize yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

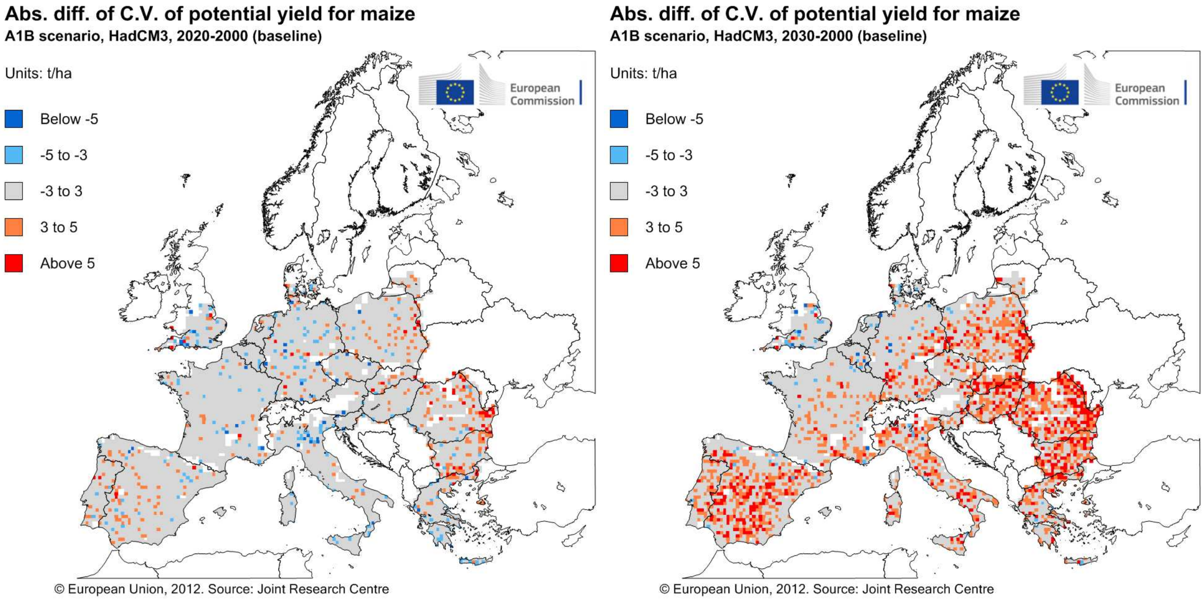


Figure 46. Change in the coefficient of variation of simulated potential grain maize yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

The reason for no change and then anticipation is due to where a substantial part of daily temperature are with respect to optimum temperature for growth; if the increase is from slightly lower than optimum temperature to slightly higher than optimum temperature, the response rate of development is symmetrically lower with respect to the optimum, showing no change in phenology. On the other hand, when the increase of temperatures is mainly for temperatures that were in the linear part of the response, an overall shortening of the cycle is caused; this is valid for all crops. The consequence shortened growth periods is an acceleration of all phenological stages, which under increased air temperatures leads to a shorter grain filling; however, in particular areas, the general anticipation of the cycle may anticipate grain filling, hence alleviating the increase of air temperature.

Water-limited yield

Water Limited production in grain maize includes rule-based irrigation to the maximum of 1500 m^3/ha, which is activated in simulations under severe stress conditions. Rules trigger irrigation when the average plant available water in the first meter of the soil profile go below 30%.
Simulation results suggest that without adaptation by 2030 water stress might be an area of concern as Southern part of Europe (Portugal, Spain, Italy, Romania and Bulgaria) are greatly affected which accounted the yield loss of 10-20%. In case of disease impact, the maize yield is slightly affected in part of Spain, Portugal, Romania and Bulgaria in 2020 but quite significantly affected in 2030 covering Spain, Portugal, Italy, Hungary, Romania and Bulgaria by 10-20% in magnitude this could be because of the favourable weather conditions that is increasing humidity and temperature. The change in response of 2030, with noticeable decreases compared to baseline, shows that the automatic irrigation (although limited) in Southern Europe areas is not adequate anymore. At the same time, being water not limiting in Northern Europe, a pattern of improvement similar to the one observed analysing potential yield is shown also under water limited conditions.

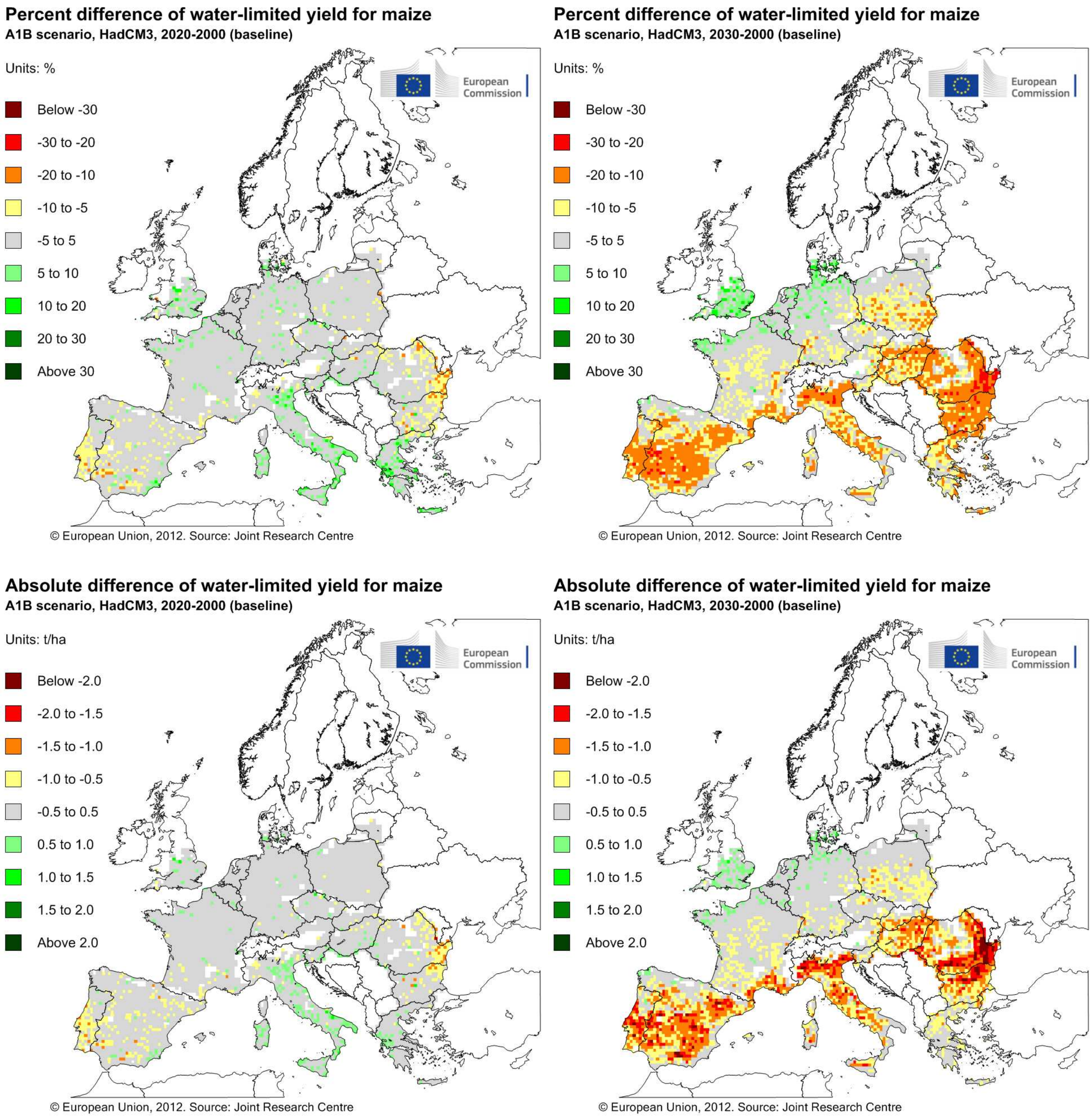


Figure 47. Change, in relative (top row) and absolute terms (bottom row), of simulated water-limited grain maize yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

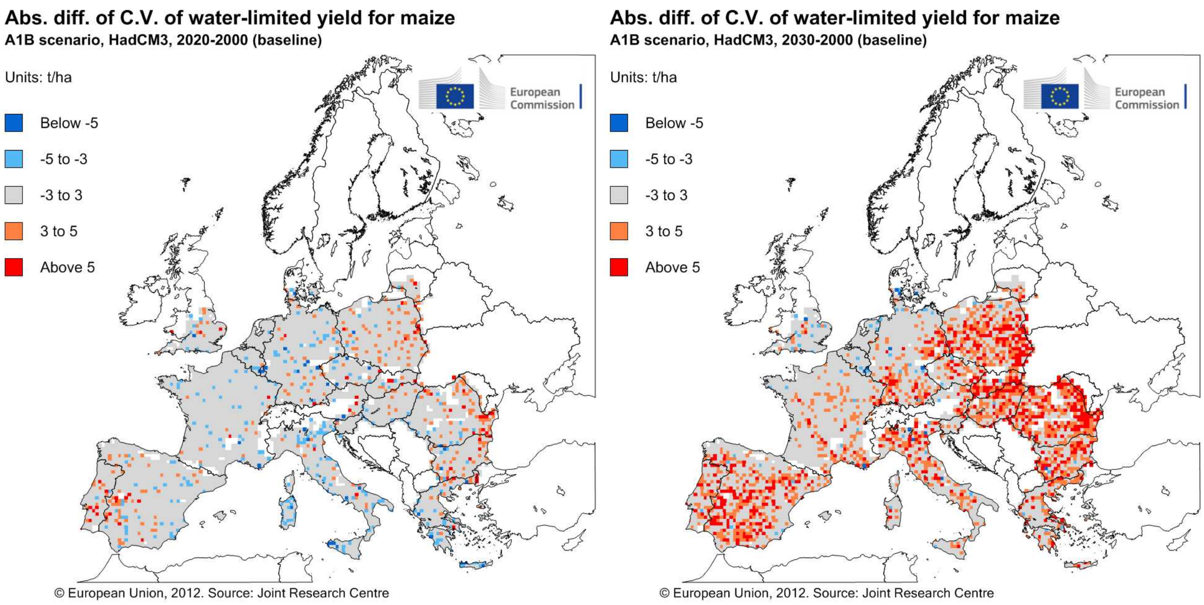


Figure 48. Change in the coefficient of variation of simulated water-limited grain maize yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Yield gaps (potential – water-limited)

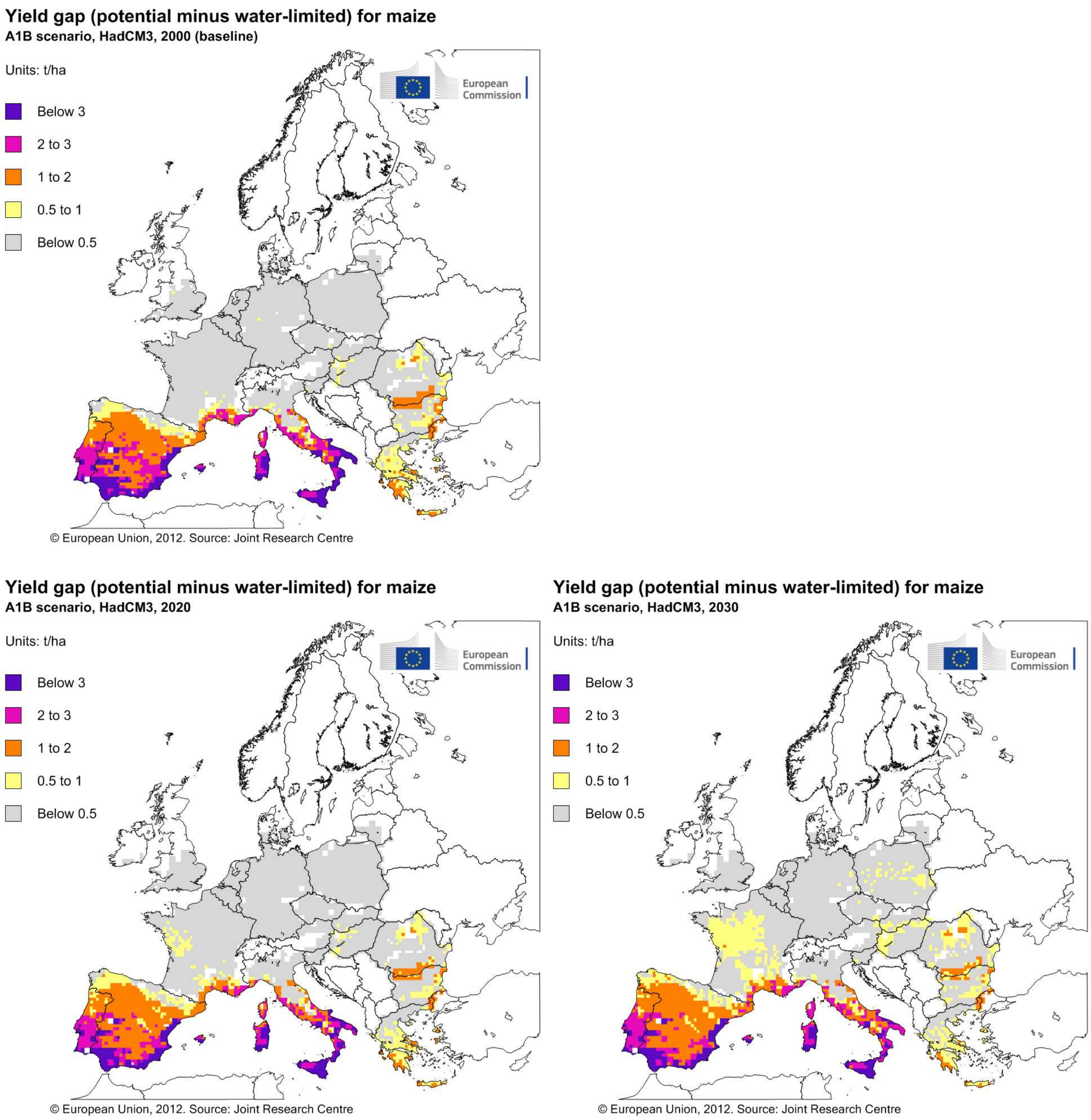


Figure 49. Grain maize yield gaps, defined as potential minus water-limited simulated yields, for different time horizons, 2000 (top), 2020 (bottom left) and 2030 (bottom right), using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Disease-limited yield

The estimates of the impact of corn grey leaf spot appear substantially unchanged in 2020, with a positive effect in North-West Europe, and negative in Southern Europe. These differences further spread in the 2030 scenario, becoming substantial.

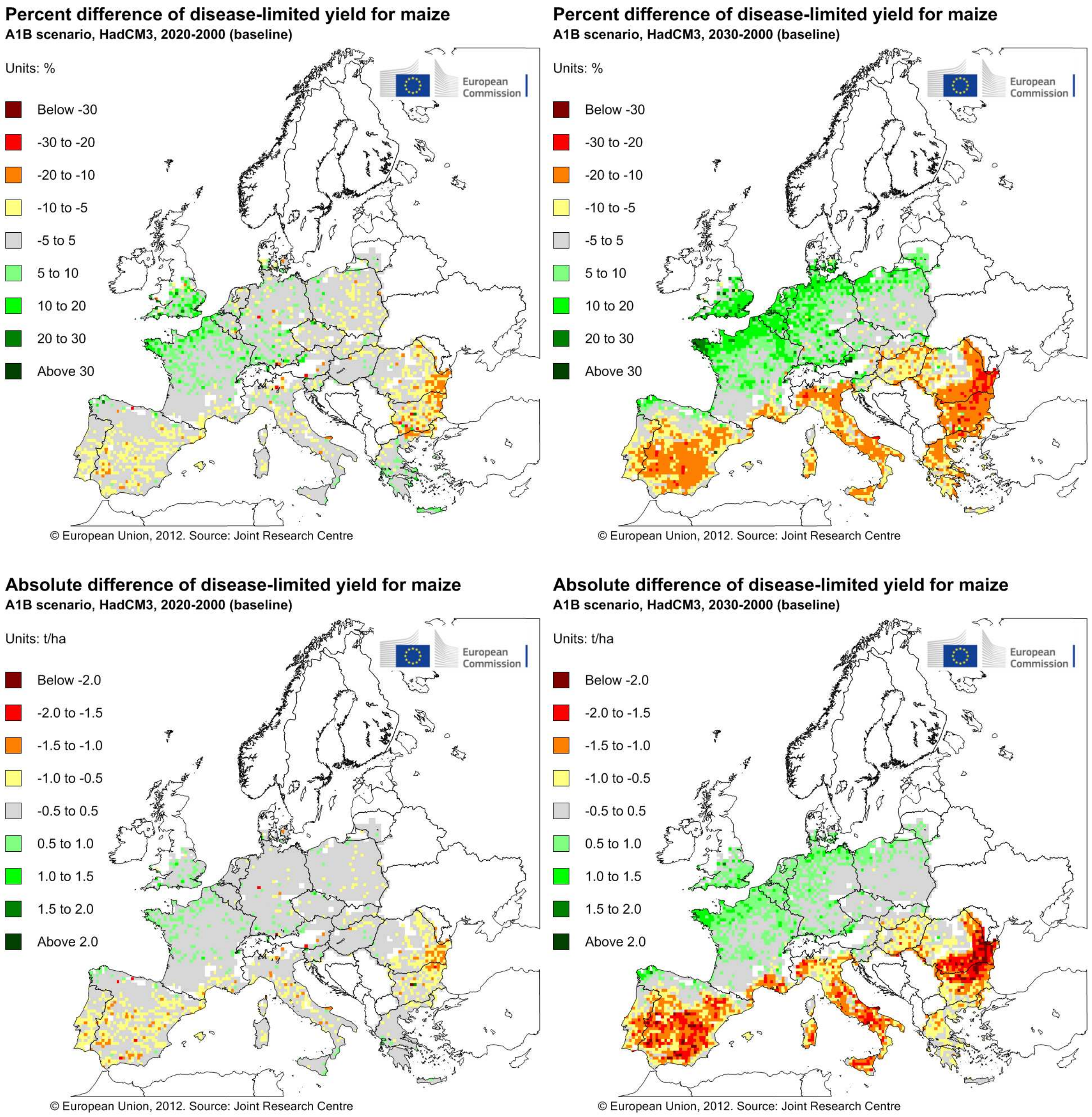


Figure 50. Change, in relative (top row) and absolute terms (bottom row), of maize simulated yield limited by disease (*Cercospora zeae-maydis*) for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Rapeseed

Potential yield

Simulation results indicate improvements in Rapeseed yield in Spain, Southern part of France and Italy by 5-10% whereas Northern France, Belgium, Netherlands, Northern Germany and UK encounter a decline ranging from 5-20% under potential conditions in the 2020 time horizon. Rest of Europe see little improvement or remain unaffected. The effect of climate change has become intense in terms of yield decline over whole Europe in general specifically in Spain and Italy. However, gain in rapeseed yield could be expected in some part of Poland and Lithuania in 2030 time window.

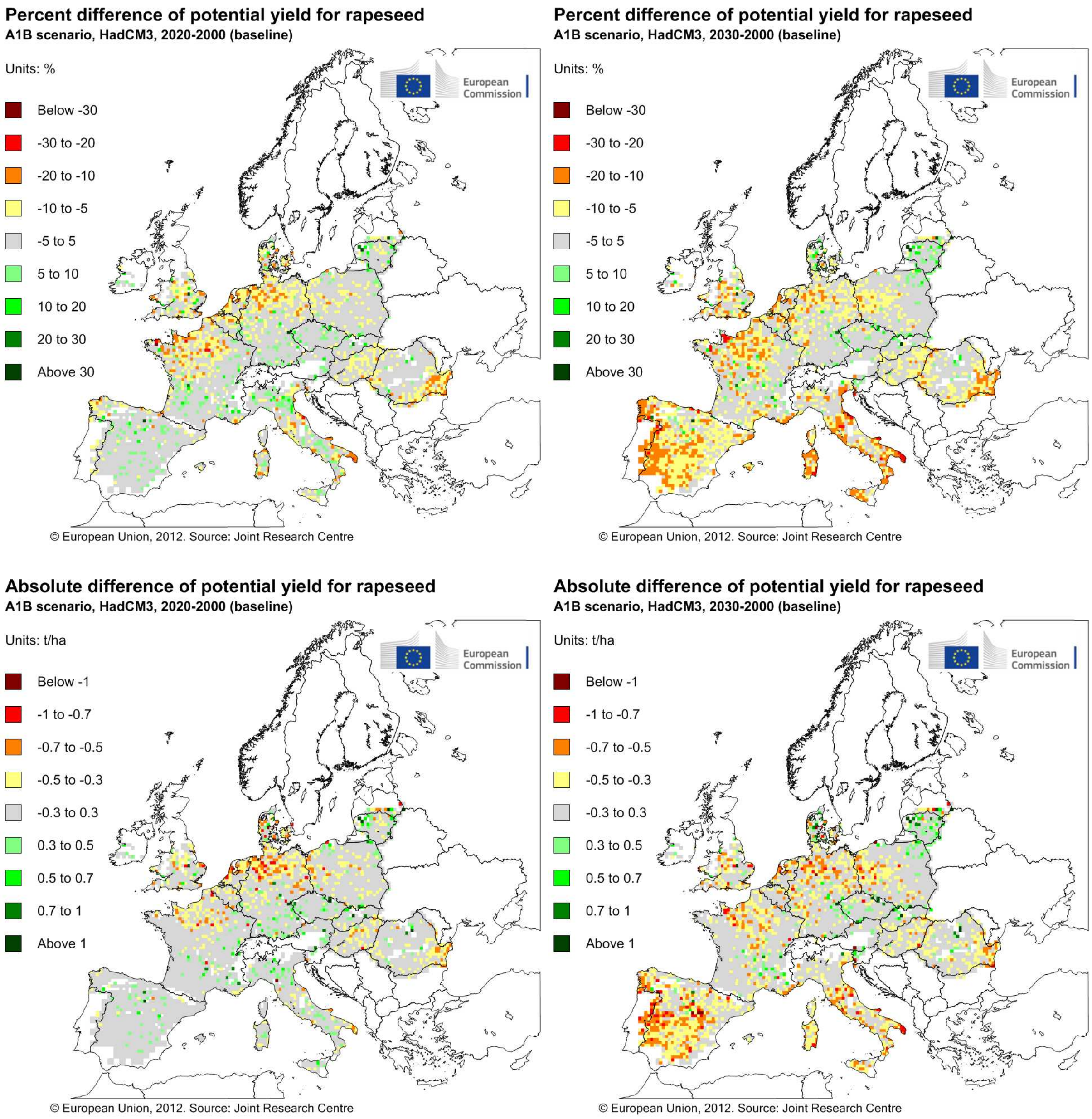


Figure 51. Change, in relative (top row) and absolute terms (bottom row), of simulated potential rapeseed yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

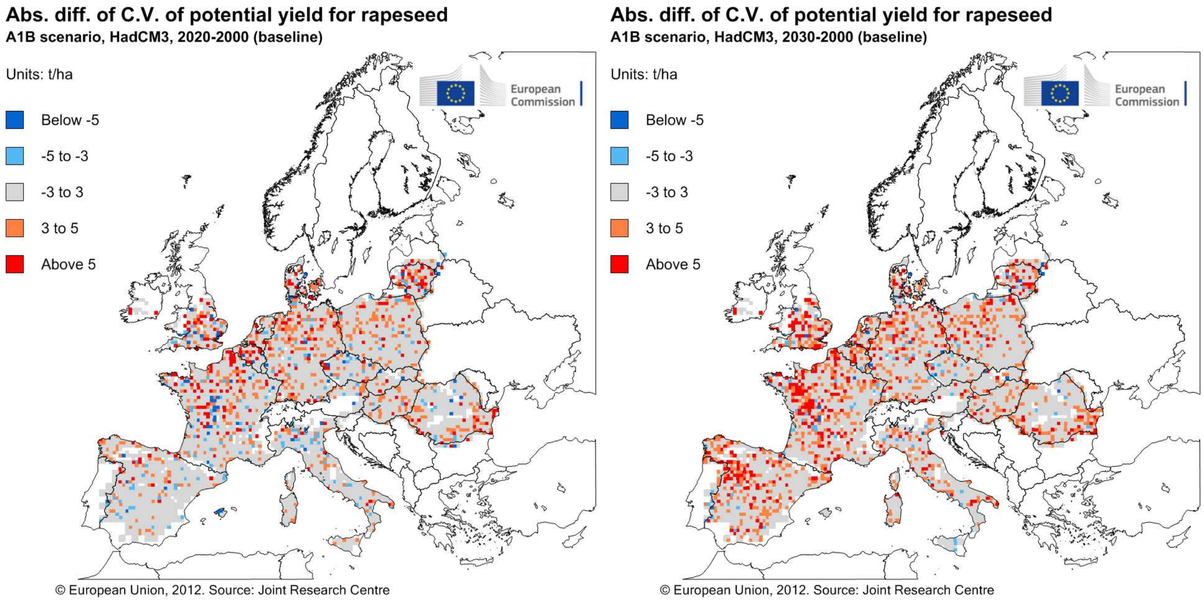


Figure 52. Change in the coefficient of variation of simulated potential rapeseed yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Water-limited yield

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 (see Absolute yield difference maps) suggests firstly, water is not a limiting factor because of higher amount of precipitation estimated by then and secondly, the positive implication of CO_2 fertilization. The disease impact on the Rapeseed yield which goes up to 30% is foreseen mainly in the Southern part of Europe namely Spain, Italy and parts of Romania perhaps favourable weather conditions that is increased humidity and temperature in these regions triggered the disease incidence.

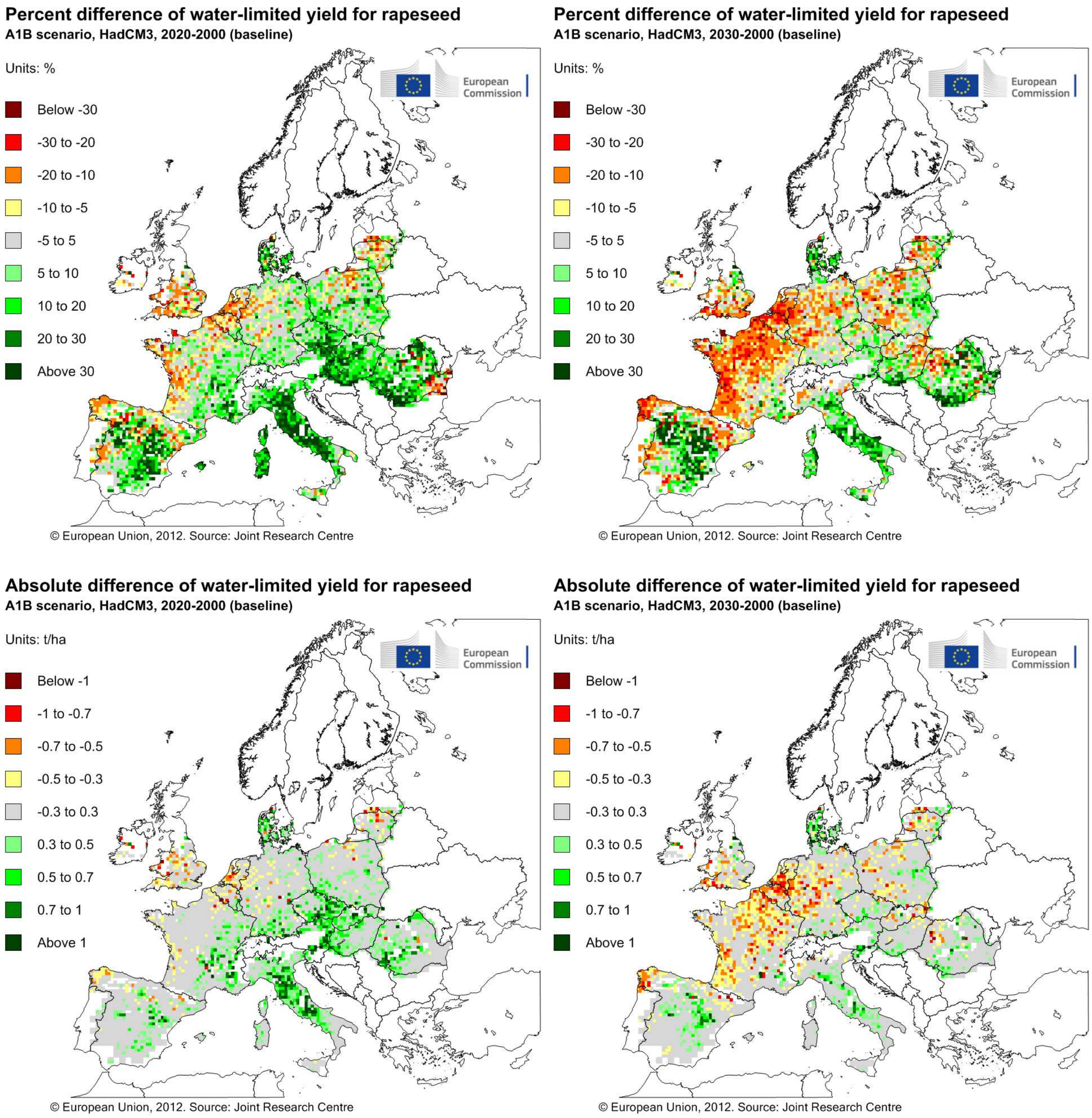


Figure 53. Change, in relative (top row) and absolute terms (bottom row), of simulated water-limited rapeseed yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

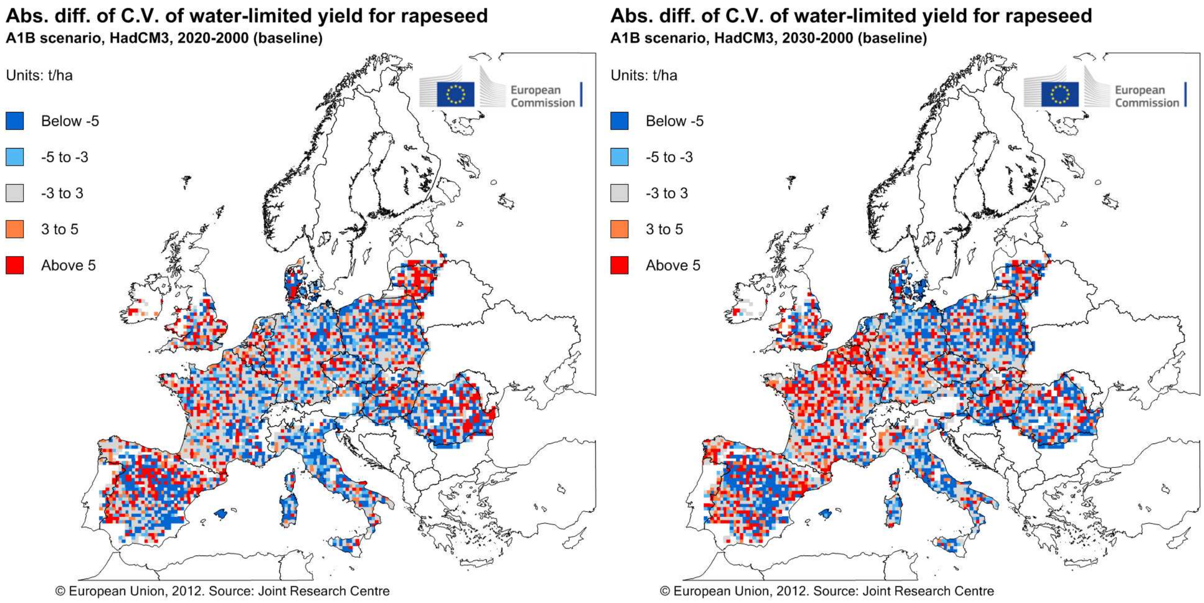


Figure 54. Change in the coefficient of variation of simulated water-limited rapeseed yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Yield gaps (potential - water-limited)

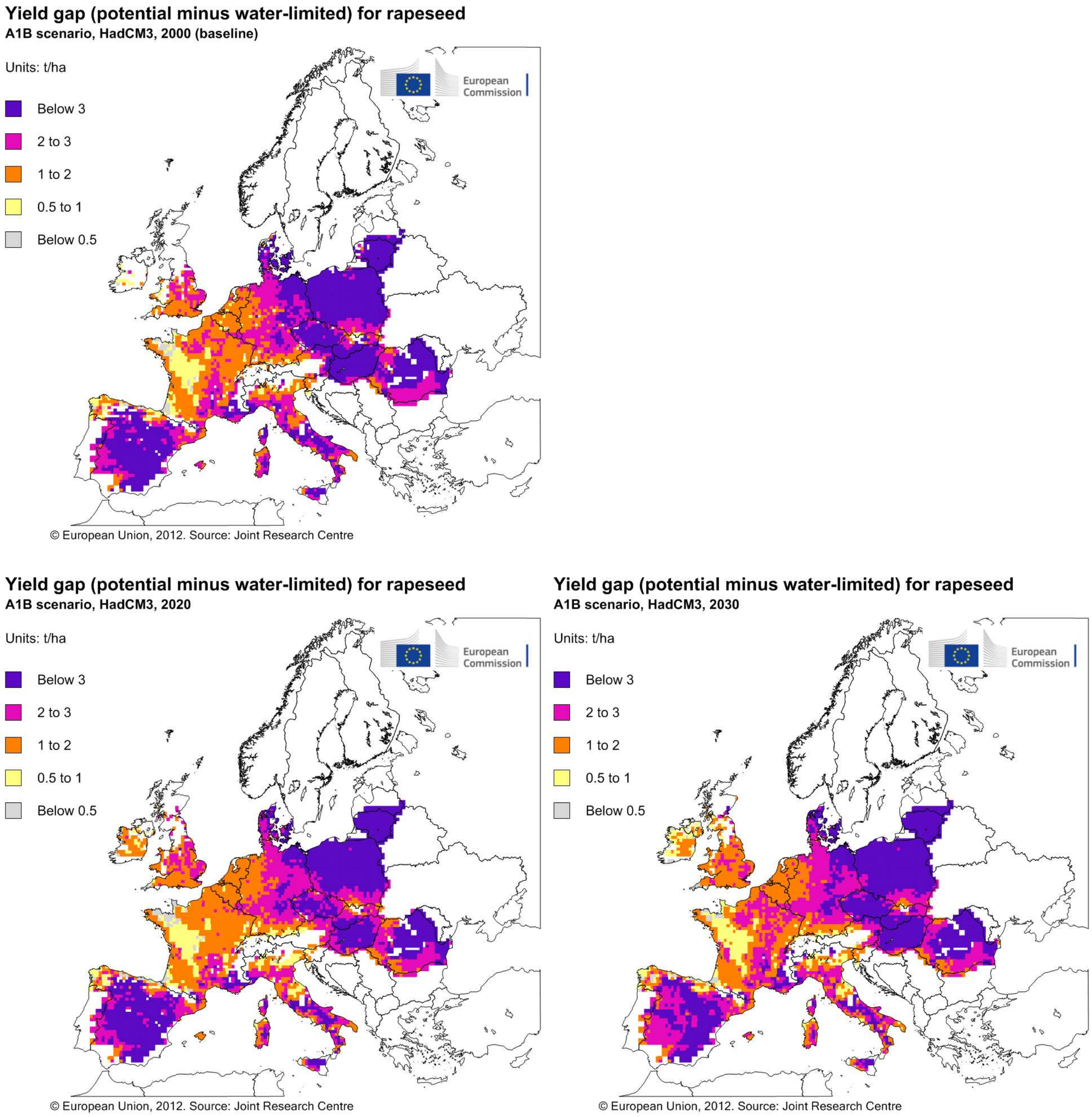


Figure 55. Rapeseed yield gaps, defined as potential minus water-limited simulated yields, for different time horizons, 2000 (top), 2020 (bottom left) and 2030 (bottom right), using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Disease-Limited

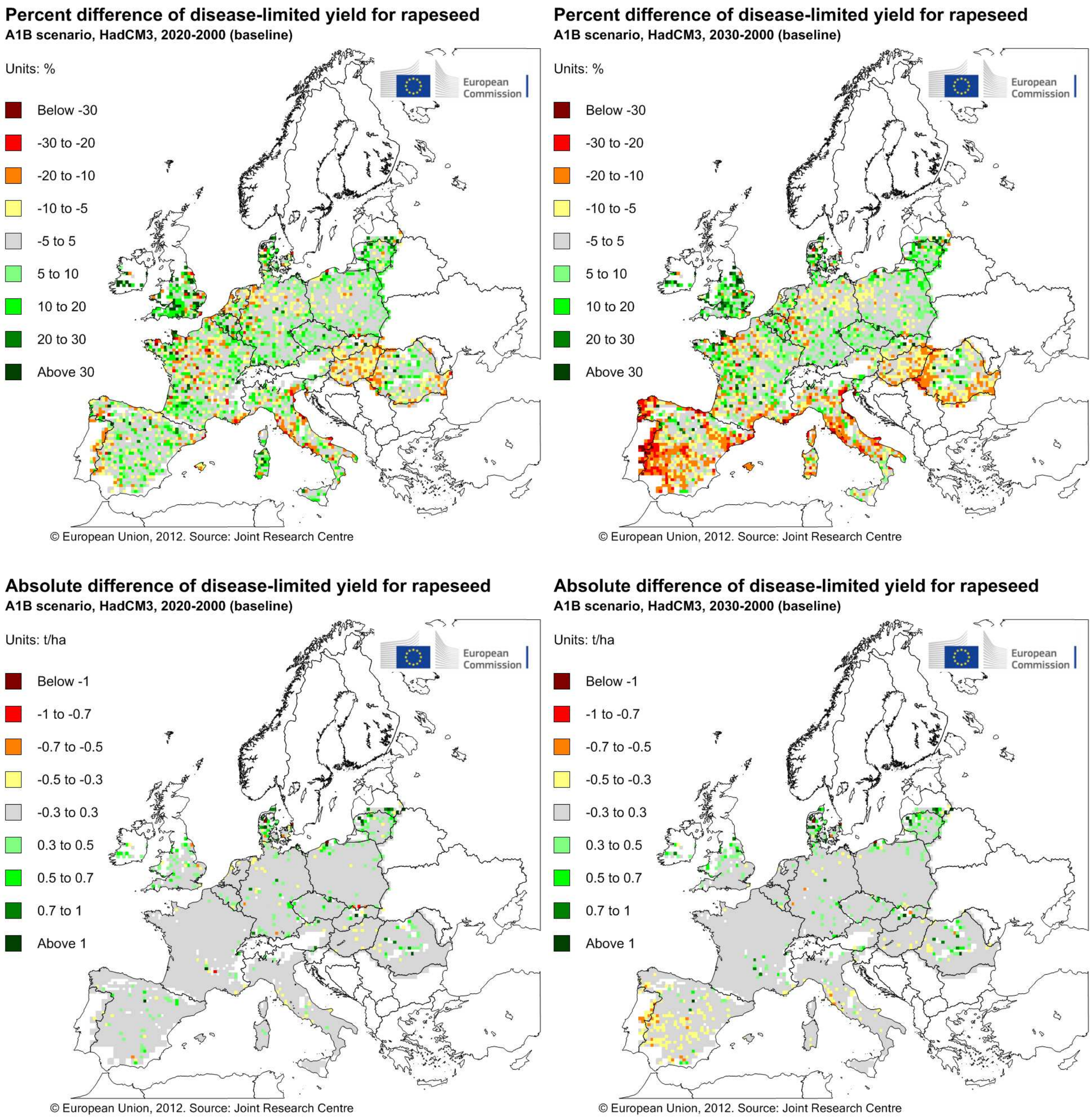


Figure 56. Change, in relative (top row) and absolute terms (bottom row), of rapeseed simulated yield limited by disease (*Alternaria brassicae*) for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Sunflower

Potential yield

Sunflower simulation results show a picture of yield improvement by 2020 compared to baseline time horizon in a magnitude of 5-10% or no change in whole Europe except decline in some places of Portugal, Romania and Bulgaria which is not substantial. Whereas, in 2030 time window, the detrimental effect of climate change is mainly concentrated on Southern part of Europe comprising Spain, Italy, Hungary, Romania and Bulgaria by 5-20% which might be due to the fact that high average "seasonal" temperatures can increase the risk of drought, limit the photosynthetic rates and also reduce light interception by accelerating phenological development. In contrary the yield gain in Northern France, Germany suggests that the negative impacts of higher seasonal temperatures are less pronounced in this part of world where global warming may increase the length of the growing period and render suitable condition for Sunflower.

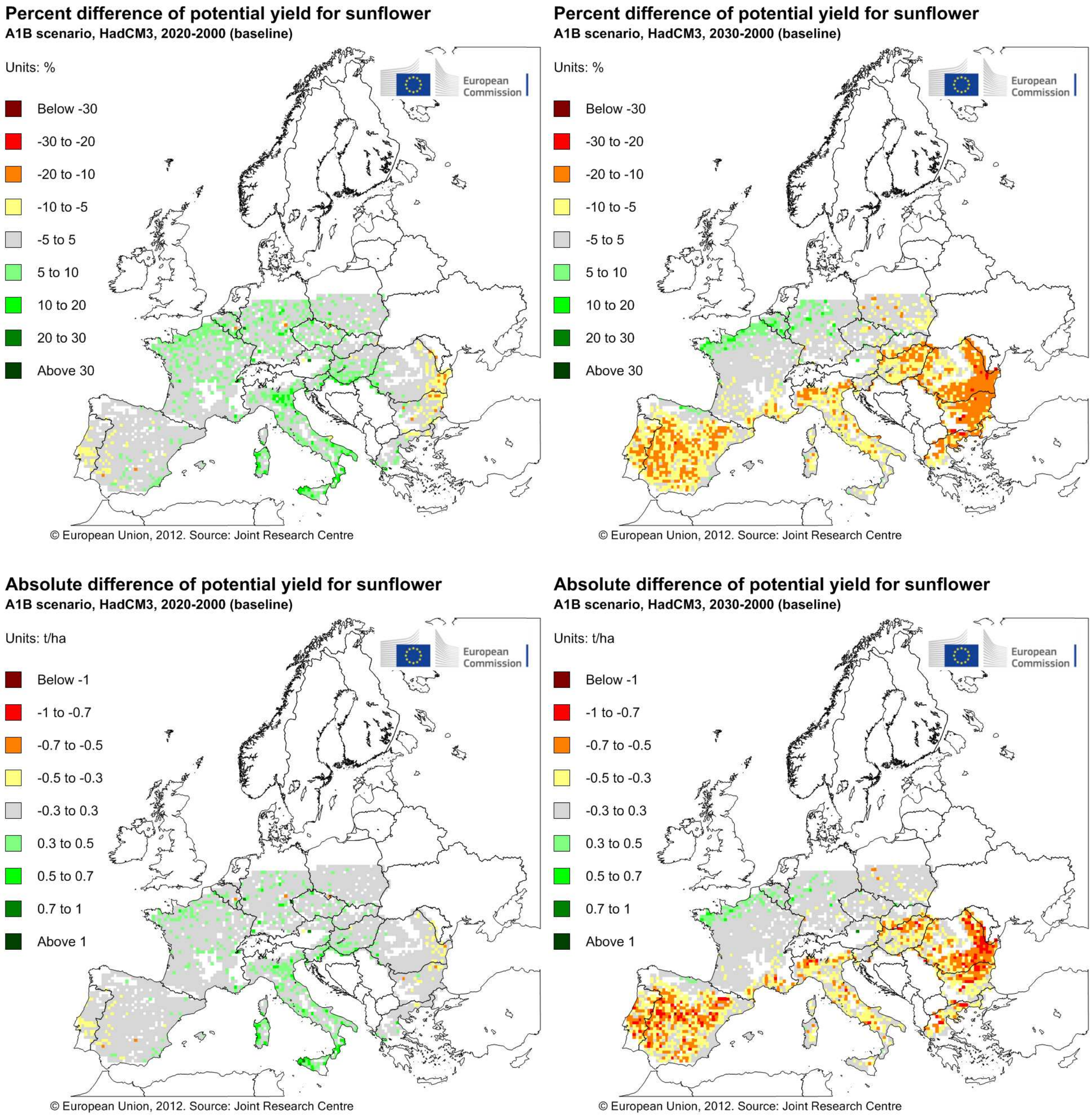


Figure 57. Change, in relative (top row) and absolute terms (bottom row), of simulated potential sunflower yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

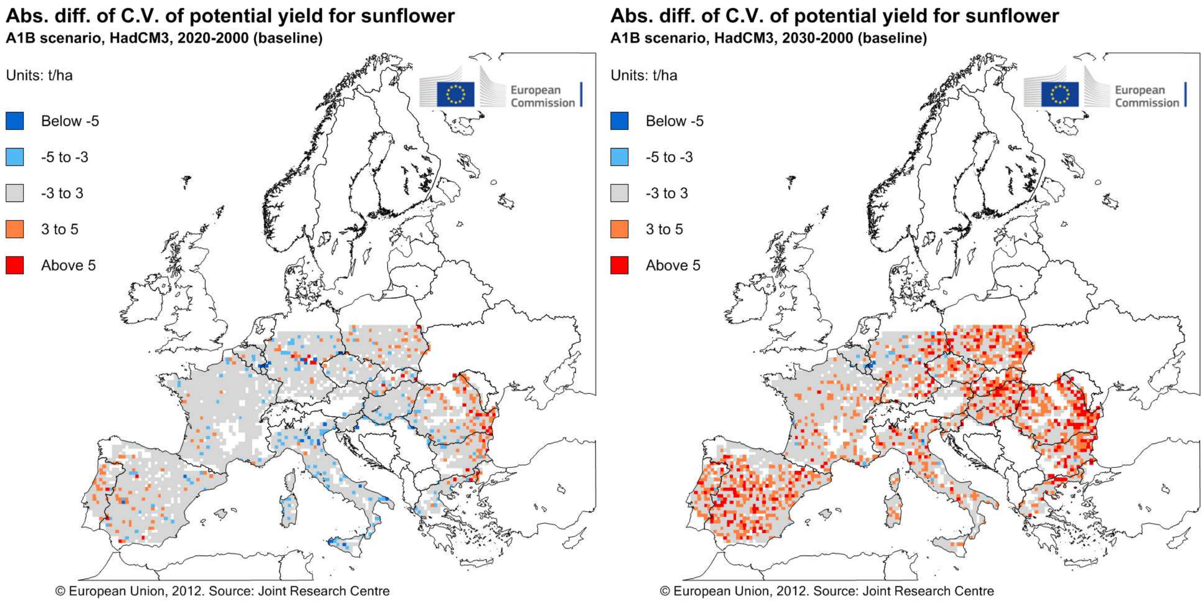


Figure 58. Change in the coefficient of variation of simulated potential sunflower yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered

Water-limited yield

The simulation result shows remarkable improvement in sunflower yield in Spain, Italy, Romania and Bulgaria (in general area in Southern latitude) with some patches of decline in France and Germany in 2020 compared to the baseline time horizon.

The improvements can directly be linked to the higher precipitation compared to baseline (see cumulated precipitation maps). 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.

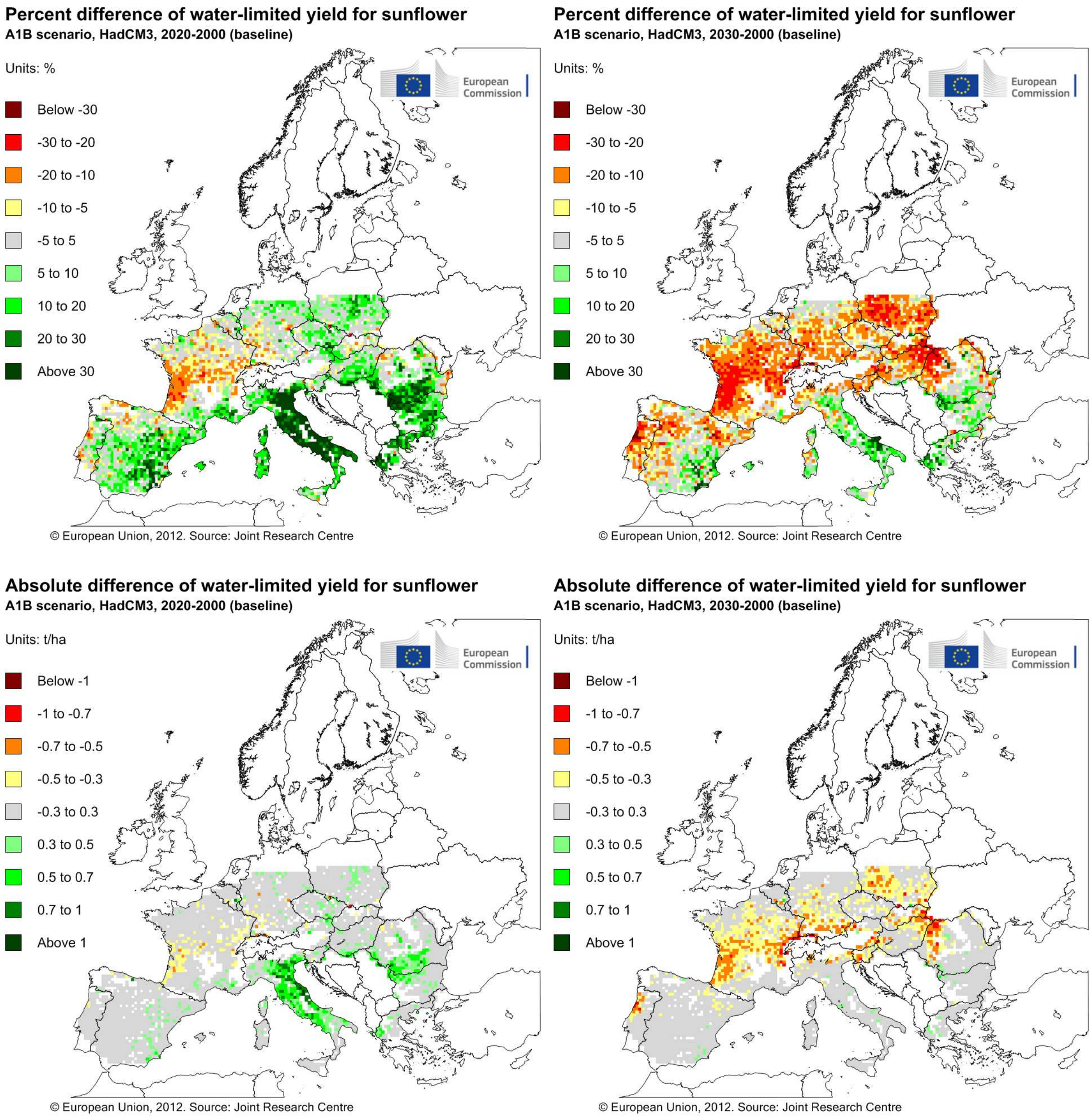
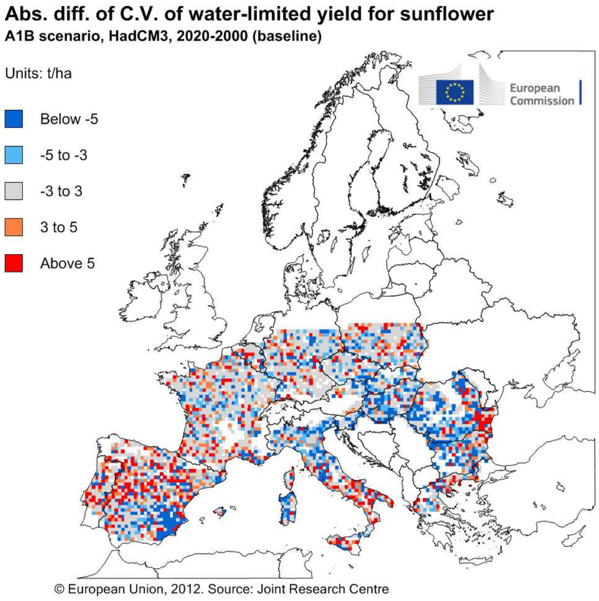


Figure 59. Change, in relative (top row) and absolute terms (bottom row), of simulated water-limited sunflower yield for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.



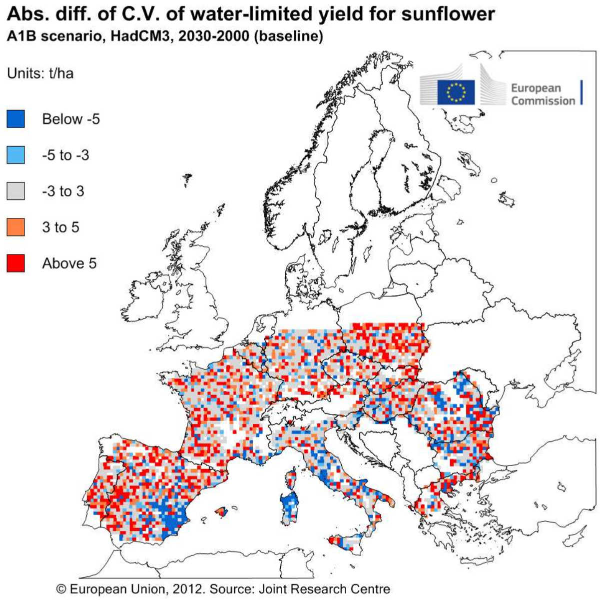


Figure 60. Change in the coefficient of variation of simulated water-limited sunflower yield for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Yield gaps (potential - water-limited)

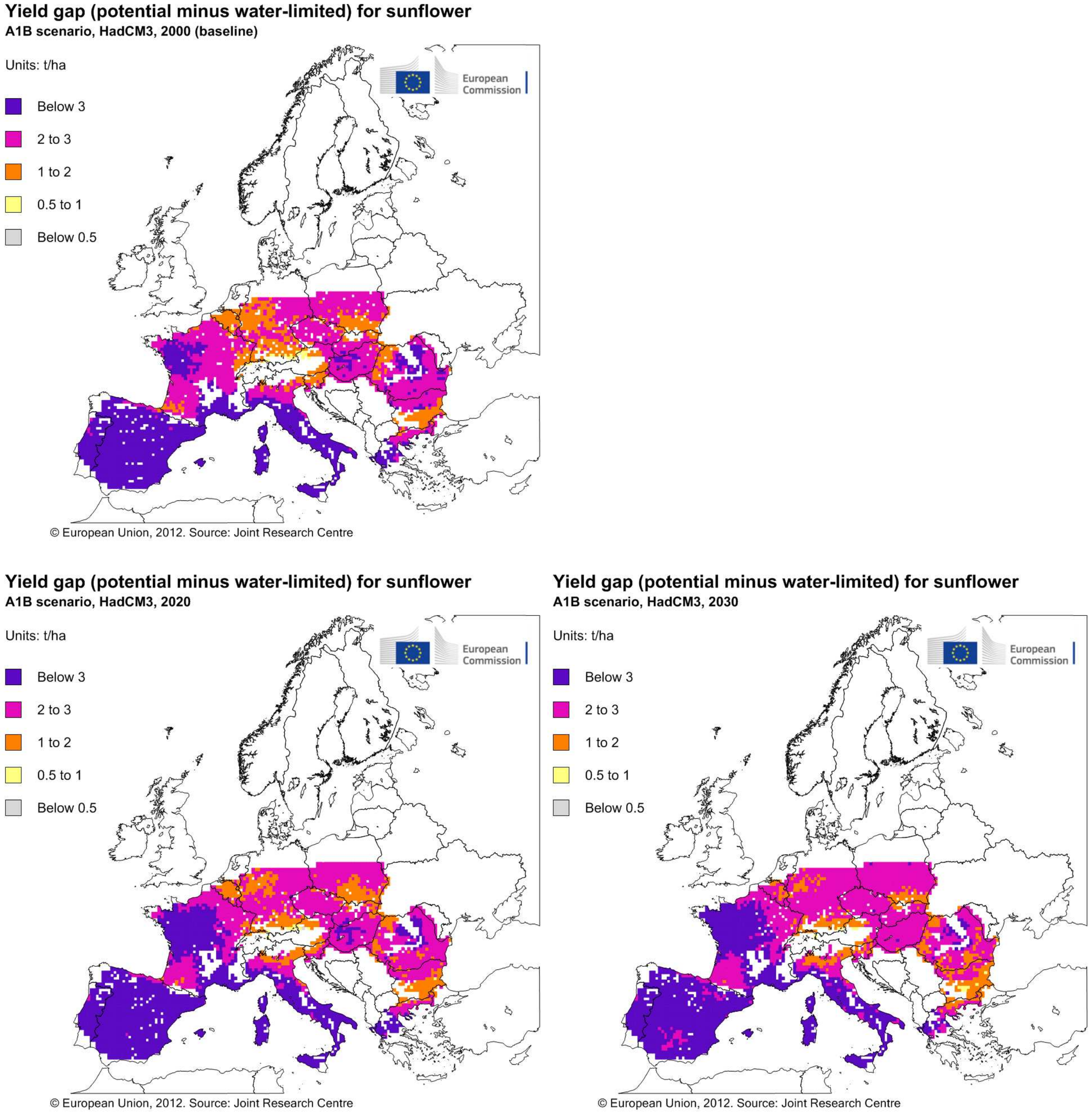


Figure 61. Sunflower yield gaps, defined as potential minus water-limited simulated yields, for different time horizons, 2000 (top), 2020 (bottom left) and 2030 (bottom right), using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Disease-limited

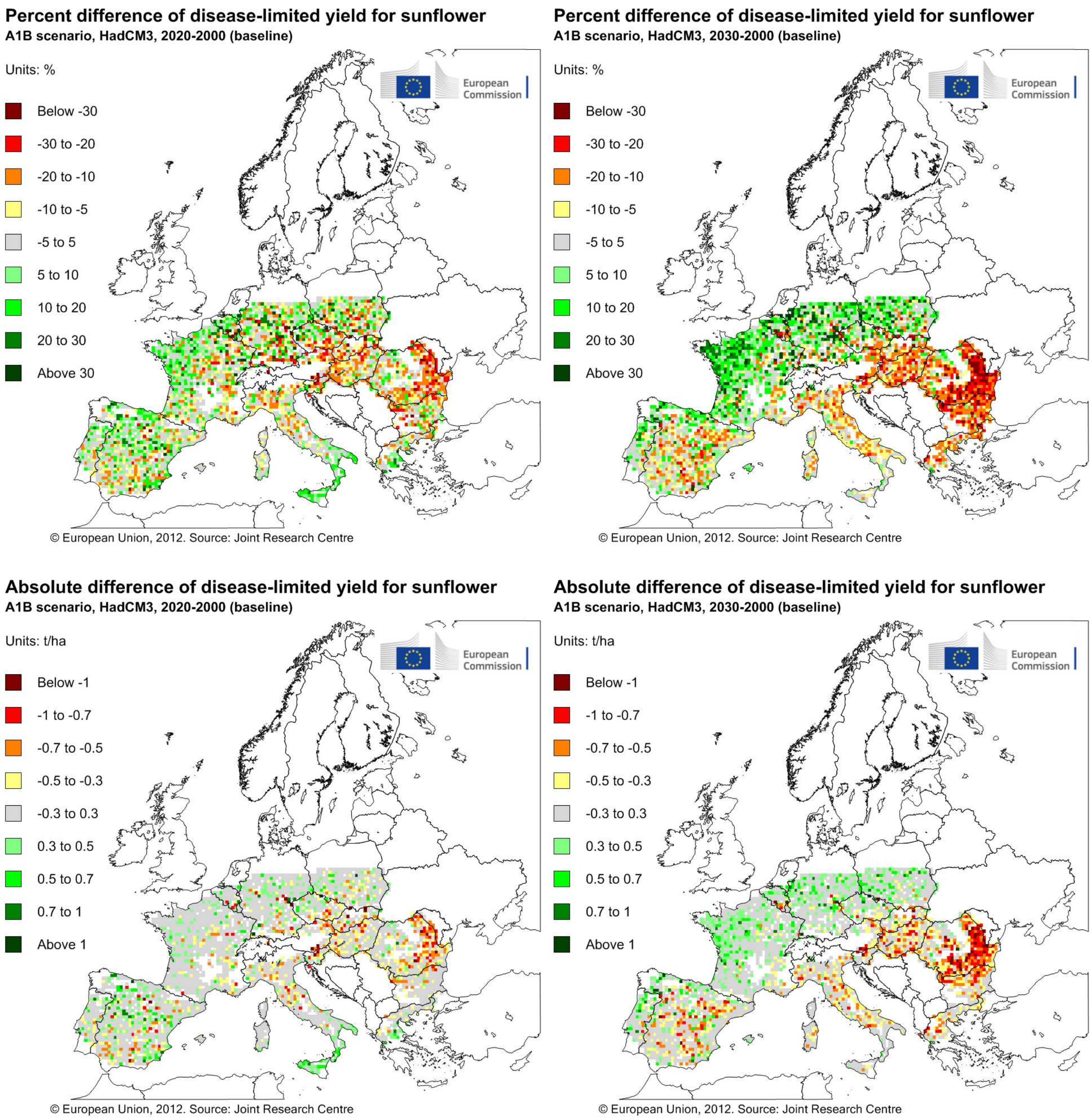


Figure 62. Change, in relative (top row) and absolute terms (bottom row), of sunflower simulated yield limited by disease (*Alternaria helianthi*) for 2020 (left column) and 2030 (right column) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Rice

Potential yield

For rice, the changes in climate are not foreseen to affect significantly its yield. Improvements in yield can be expected in parts of North-Western Italy, Hungary and Bulgaria whereas yield estimates remain unchanged in rest of the simulated area with some decline of 5-10% in parts of Southern Spain, Romania, Bulgaria and Greece. Generally, the increased yield can be explained by the fact that current temperature conditions are still below the optimal and increasing temperatures in future climate scenarios would provide better growing conditions whereas decline concentrated on the Southern latitude in mentioned countries could be result of water stress.

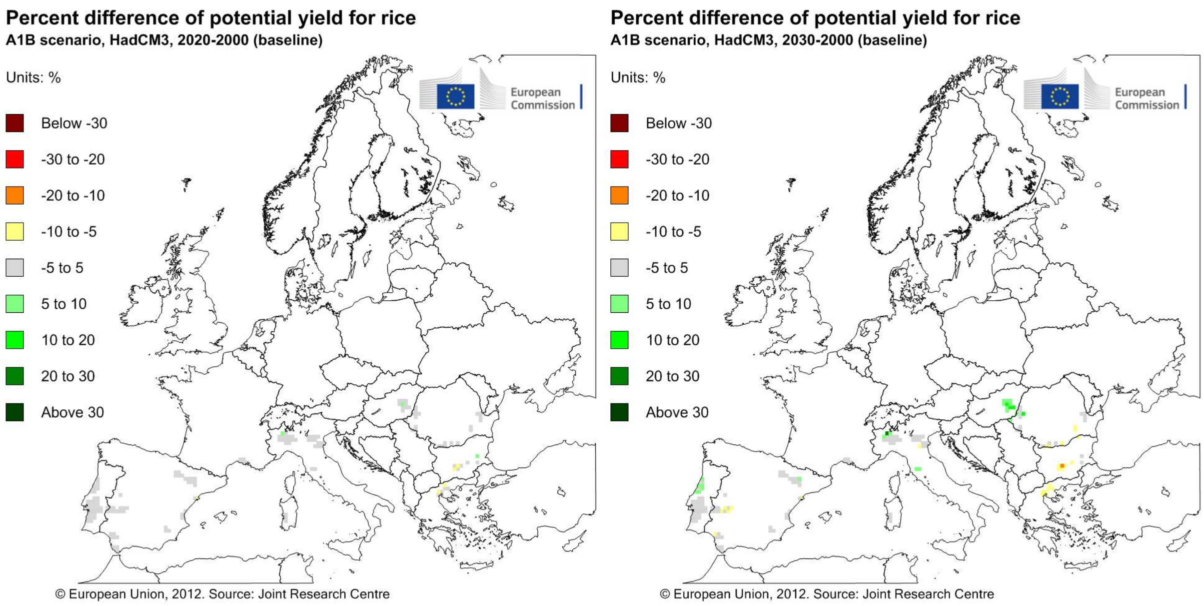


Figure 63. Percent change in simulated potential yield for rice for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Disease-limited yield

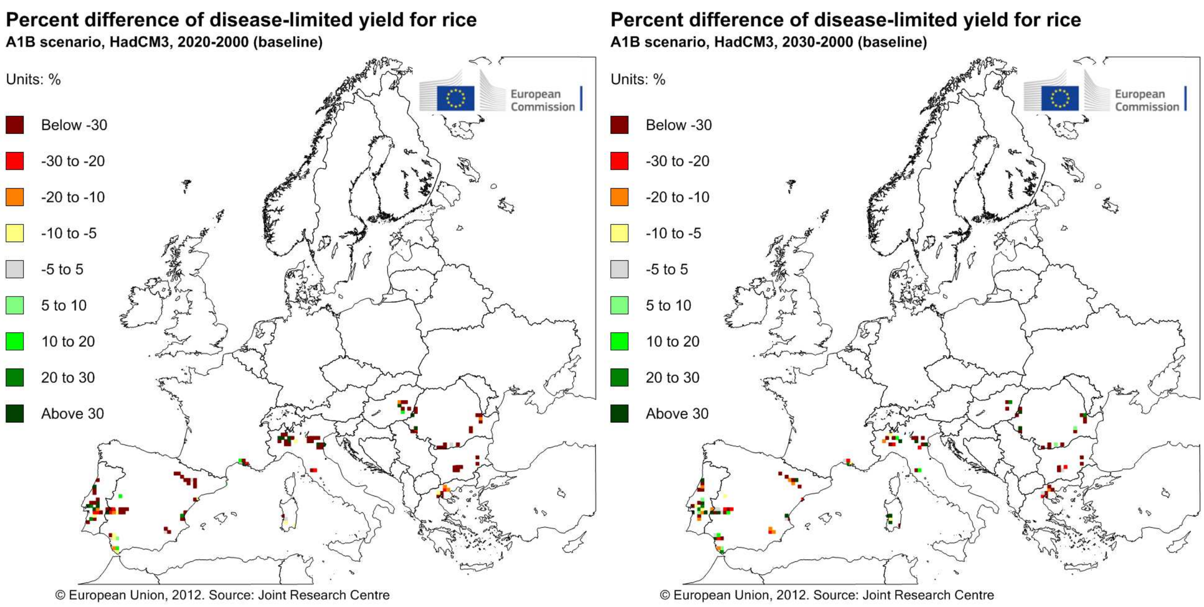


Figure 64. Percent change in simulated yield for rice limited by disease (*Pyricularia oryzae*) for 2020 (left) and 2030 (right) using the 'warm' (HadCM3) realization of scenario A1B. No adaptation strategies are considered.

Grapevine phenology

Grapevine growth and development is largely driven by temperature. Figures below show changes in maturity and flowering date comparing projections in 2020 and 2050 with respect to 2000. Three varieties with different maturity cycles are shown: Syrah, Chardonnay (early maturity), and Cabernet Sauvignon (late maturity). A generalized anticipation of maturity dates is projected for most of the areas of Europe. However, in some areas of Southern Europe, where projected temperatures above an optimum become more frequent in 2050, the average rate of growth decreases and maturity is delayed. The protected designation of origin for wines is related to the peculiar combination of different factors into specific geographical areas (*terroir*): environment (soil and climate), varieties, and knowledge on agricultural and oenological practices. These projections indicate several changes to the current situation. Indeed, producers and consumers have already experienced changes in some wines, for instance in relation to alcohol content.

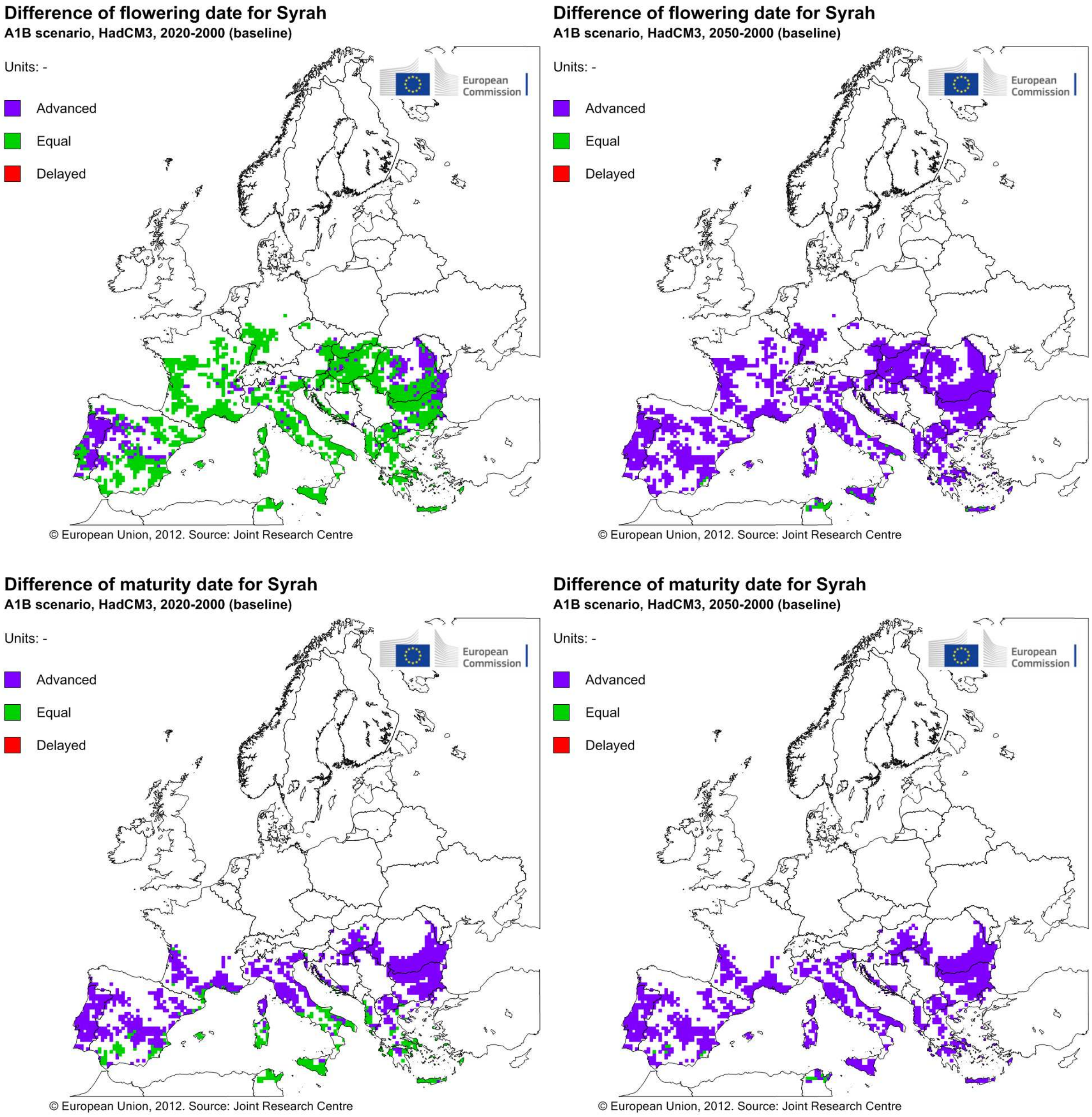


Figure 65. Shift in flowering (top row) and maturity dates (bottom row) for Syrah in 2020 (left column) and 2050 (right column) under scenario A1B with HadCM3.

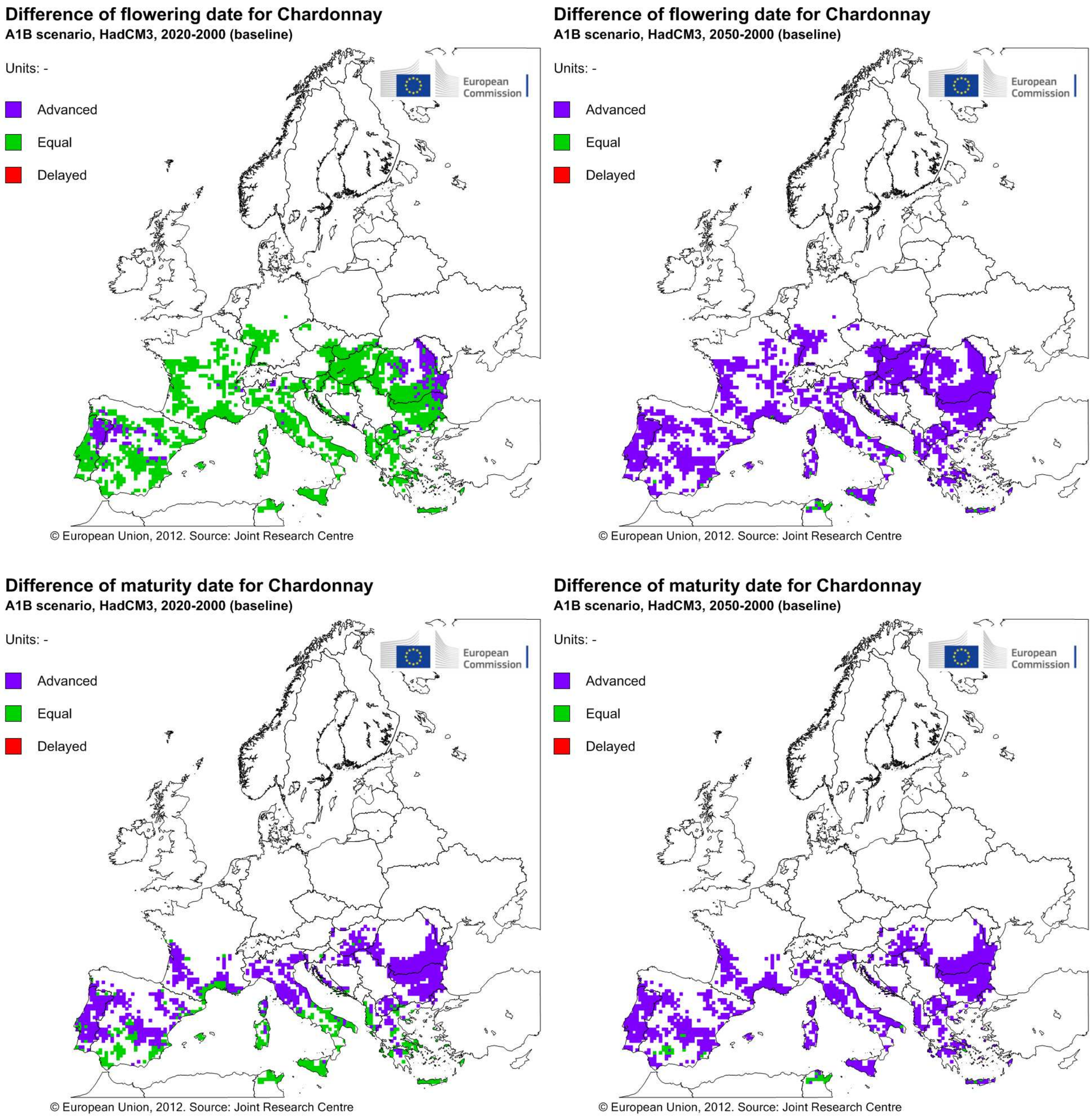


Figure 66. Shift in flowering (top row) and maturity dates (bottom row) for Chardonnay in 2020 (left column) and 2050 (right column) under scenario A1B with HadCM3.

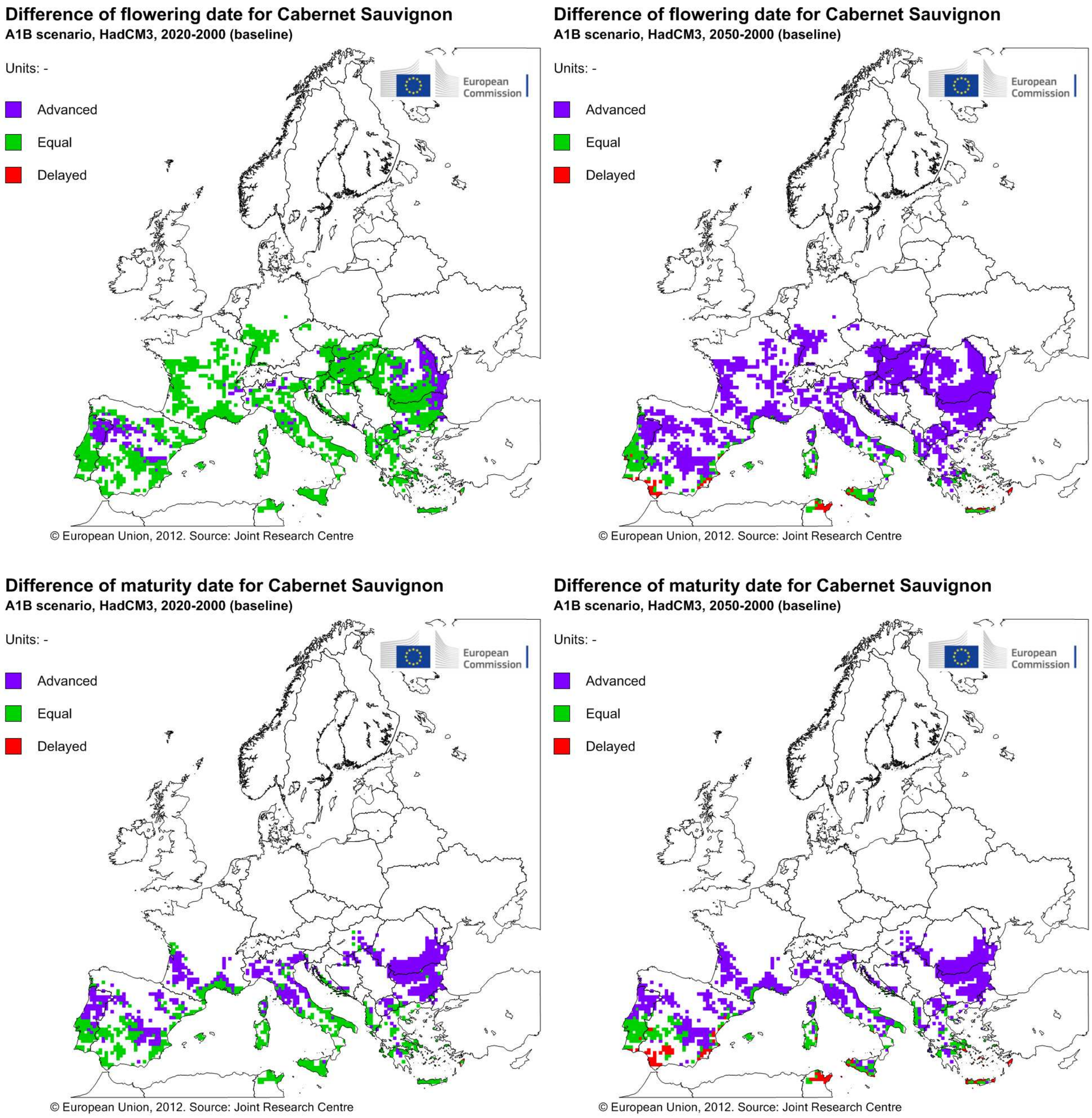


Figure 67. Shift in flowering (top row) and maturity dates (bottom row) for Cabernet-Sauvignon in 2020 (left column) and 2050 (right column) under scenario A1B with HadCM3.

ECHAM5 realization of the A1B SRES ("cold A1B")

Although this realization of A1B estimates, as average, a more modest raise of temperature compared to HadleyC3 realization, the main difference is on rainfall patterns which are substantially opposite. The lower estimate of rainfall in most of Southern Europe leads to a negative impact for most crops.

Wheat

Potential

In 2020 time horizon, the simulation results under potential condition indicate improvement in the yield by 5-10% mainly in Ireland, UK, France, Belgium, Netherlands parts of Germany and Italy. The rest of EU-27 states see no detrimental impact of climate change when compared to baseline period. The improvement in yield could be a result of no change in temperature and increased precipitation. Whereas, by 2030 the improvement in yield disappears from the noted regions, resultant of less precipitation compared to baseline and increased temperature that anticipated the crop phenology.
Evaluating the simulation results for 2020 time horizon under water-limited conditions depict an improvement of wheat yield in North-West European states ranging from 5-10% compared to the yields in the baseline period which may be correlated to the fact that there is increased amount of precipitation coupled with almost no change in temperature in the specified regions, whereas on contrary the southern part shows considerable yield loss which goes up to 30% mainly in Portugal, Spain and parts of Italy that get milder by 2030 time horizon probably due to the combined effect of avoidance of crop stress period due to shortening of phenology and increased CO_2 concentration.

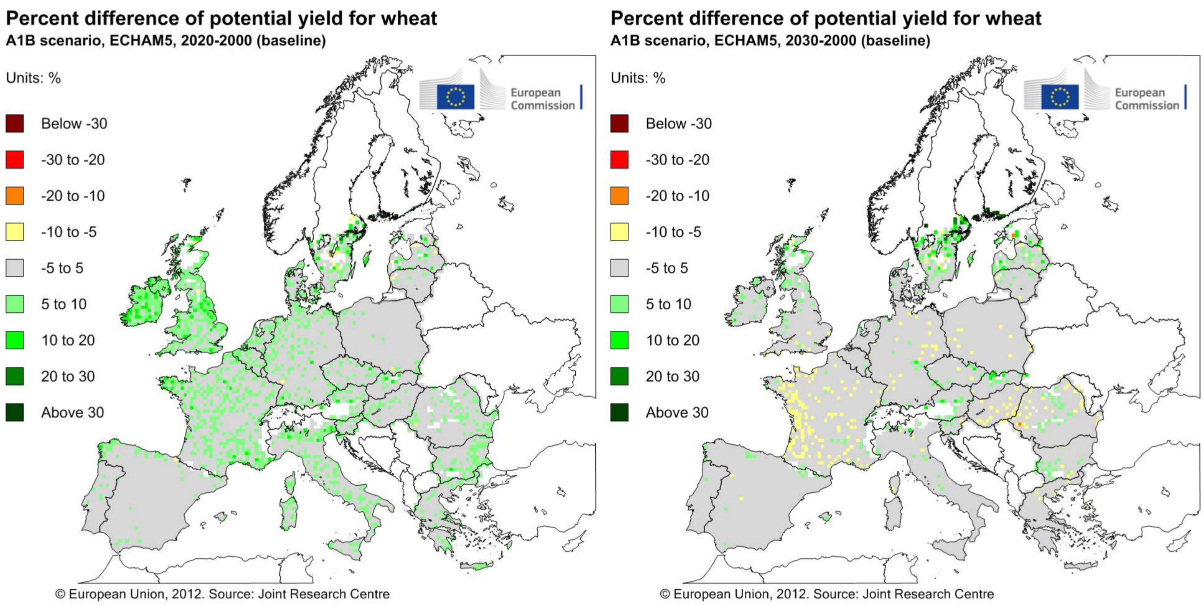


Figure 68. Percent change in simulated potential yield for wheat for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

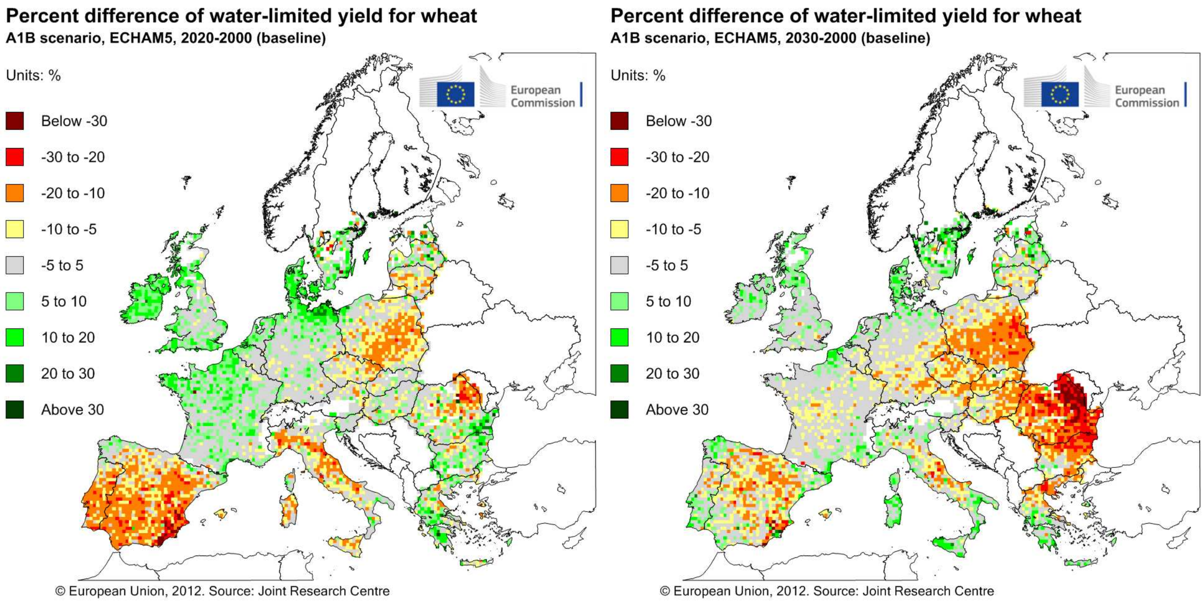


Figure 69. Percent change in simulated water-limited yield for wheat for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

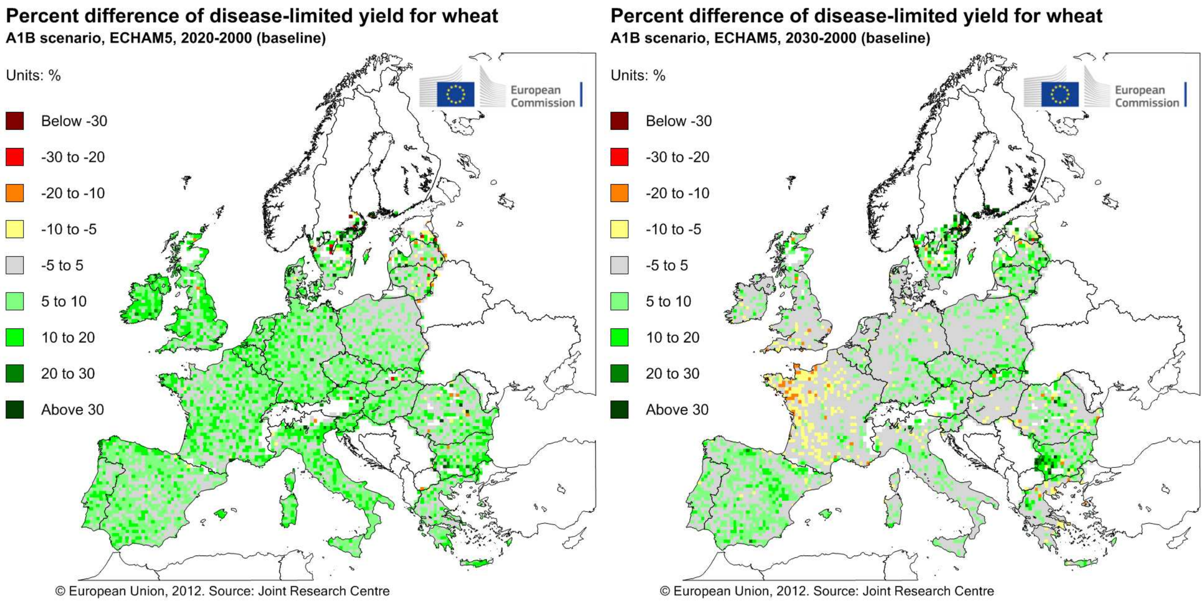


Figure 70. Percent change in simulated yield for wheat limited by disease (*Puccinia recondita*) for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Maize

Potential

In 2020, there is a general tendency of either improvement or no change in the maize yield over whole EU-27 member states except countries situated at Southern latitudes (Portugal, Spain and parts of Italy) which anticipates declined yield in the range of 5-20% whereas moving to 2030 time horizon, the same pattern is expected as was in 2020. The evaluation of simulation results under water-limited conditions indicates that the southern parts of Spain might get affected by 2030, accounting a yield loss of 10-20%. This decline compared to baseline points out firstly that there is 15-50 mm less precipitation in Spain when compared to baseline. Secondly, the irrigation amount, although limited, applied in the simulations is not enough to meet out the crop demands which is not the case for other countries in the same belt thereby anticipating significant yield gains.

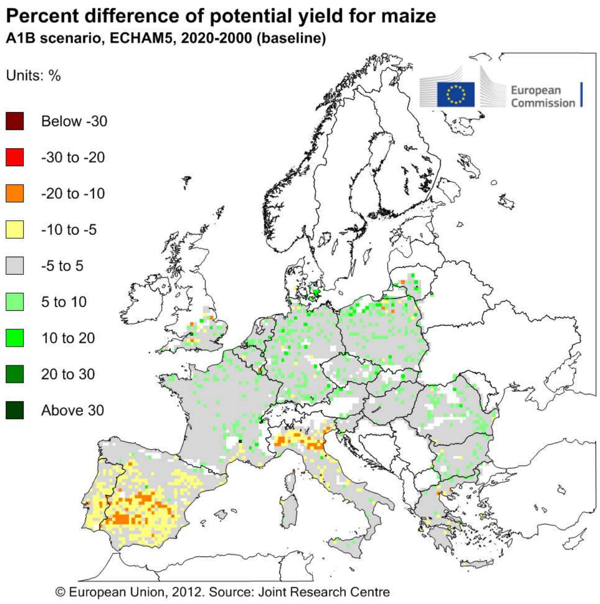


Figure 71. Percent change in simulated potential yield for maize for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Water-Limited

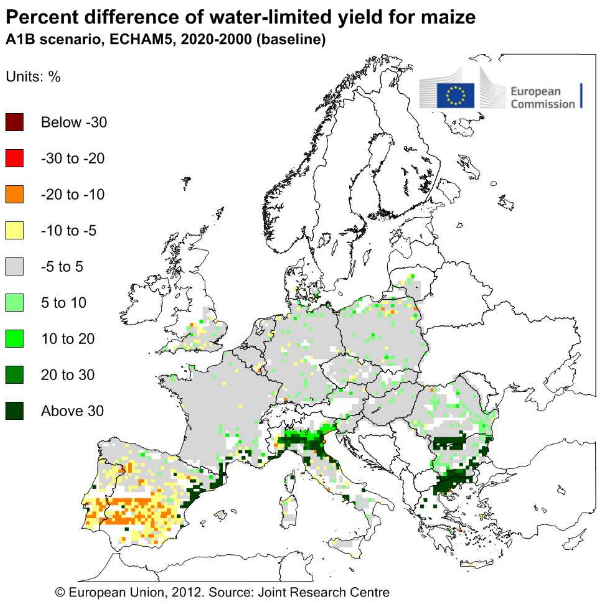


Figure 72. Percent change in simulated water-limited yield for maize for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Disease-Limited

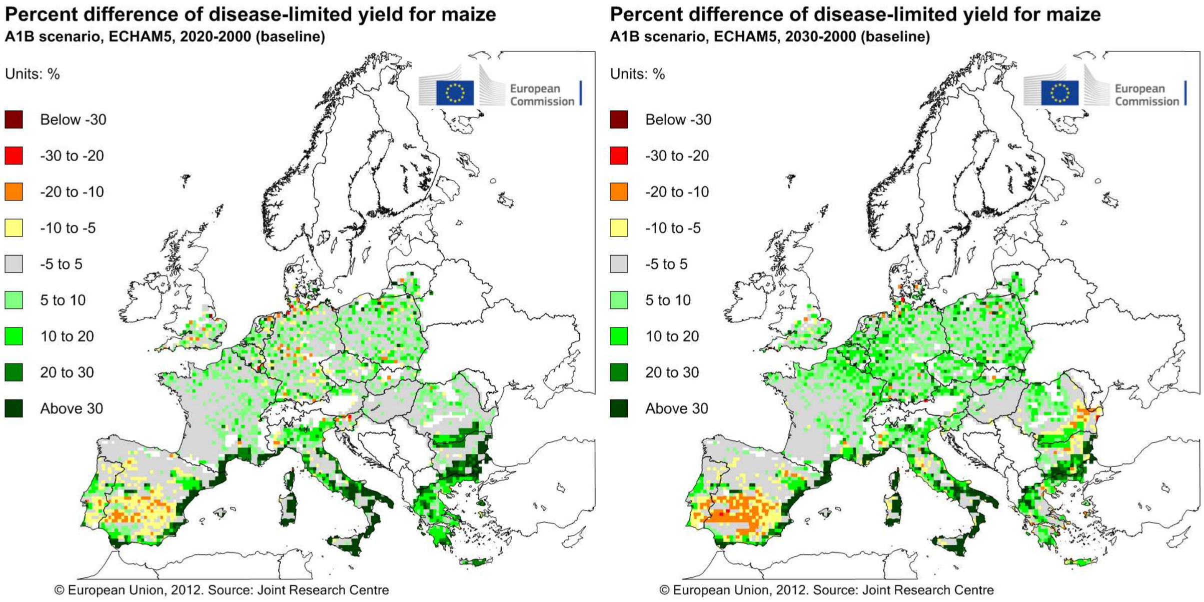


Figure 73. Percent change in simulated yield for maize limited by disease (*Cercospora zeae-maydis*) for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Rapeseed

Potential

Substantial improvement in rapeseed yield is expected over whole EU27 Member States, France in particular, by 2020 time horizon which could be related to the increased amount of precipitation (50-100 mm) and hardly any change in the temperature compared to the baseline. Whereas analysing the simulation results in 2030 time horizon, the positive impact of climate change has become confined mainly to the states situated on the northern latitude as expected. The detrimental effect on rapeseed yields on the Southern latitude states comprising of Spain, Italy, Hungary and Romania could be a result of remarkable decline in precipitation amount which goes up to 100 mm.

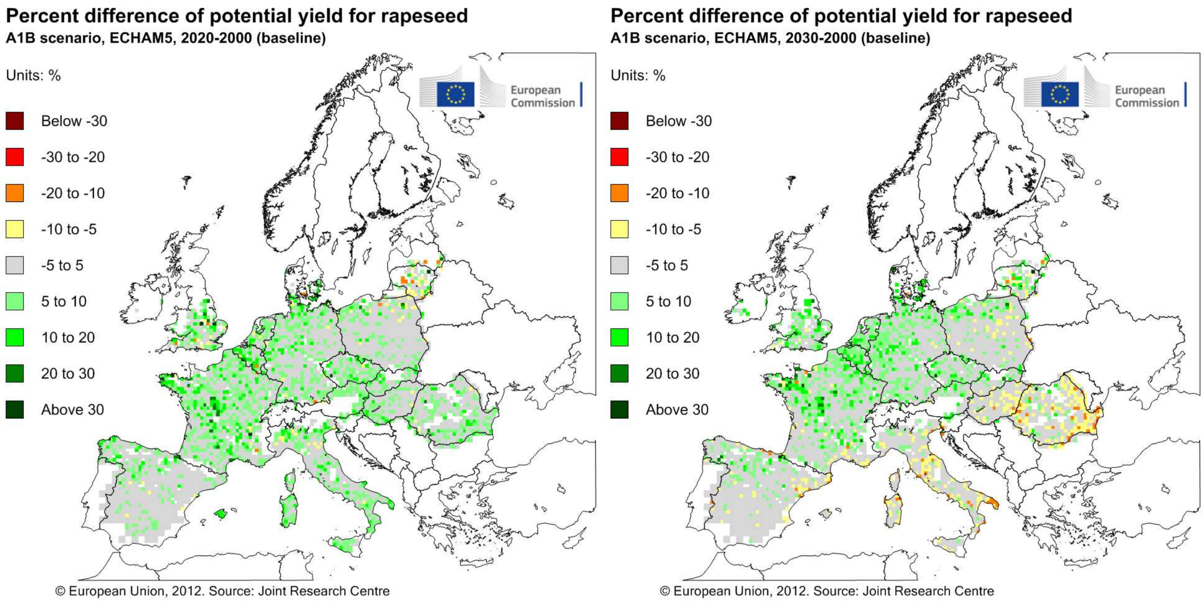


Figure 74. Percent change in simulated potential yield for rapeseed for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Water-Limited

There is an indication from the simulation results that in 2020 time horizon, there is likely yield improvements in northern latitudinal states in general whereas, in the southern latitude water stress is emerging as a prime concern for Rapeseed. A decline in the rapeseed yield up to 30% is anticipated which get less pronounce by 2030 in Spain and Italy which is related to the higher amount of precipitation foreseen in the concerned region (refer weather maps). There are chances of disease incidence accounted up to 20% yield loss mainly in the Southern part of Europe namely Spain, Italy, parts of France and Hungary perhaps favourable weather conditions mainly higher temperature in these regions is the factor.

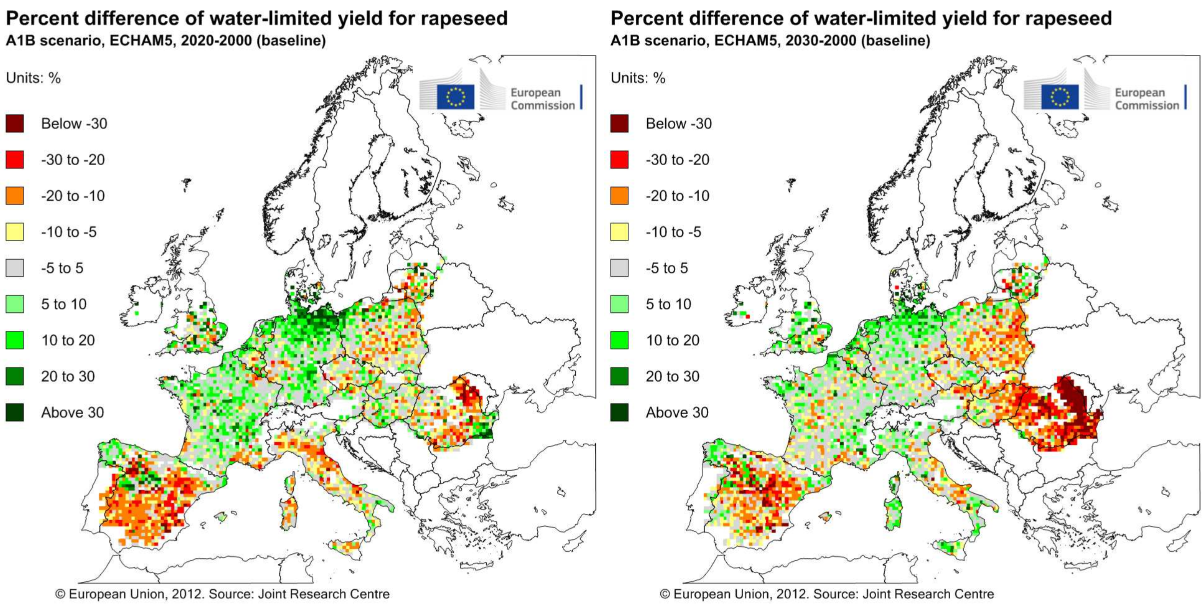


Figure 75. Percent change in simulated water-limited yield for rapeseed for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Disease-Limited

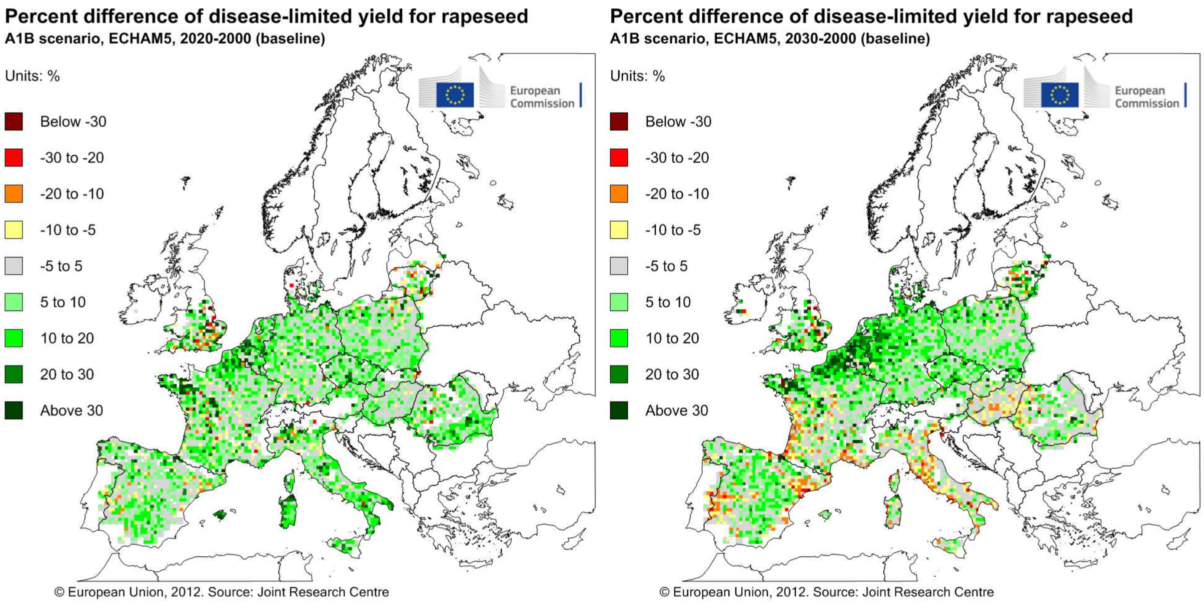


Figure 76. Percent change in simulated yield for rapeseed limited by disease (*Alternaria brassicae*) for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Sunflower

Potential

Sunflower simulation results show a picture of yield improvement by 2020 compared to baseline time horizon in a magnitude of 5-10% or no change in whole Europe except decline in parts of Portugal, Spain, Italy which is not substantial. Whereas, in 2030 time window, the detrimental effect of climate change get extended to parts of Hungary, Romania, Bulgaria and Greece which might be due to the fact that high average "seasonal" temperatures can increase the risk of drought, limit the photosynthetic rates and also reduce light interception by accelerating phenological development. In contrary the yield gain in Northern France and Germany suggests that the negative impacts of higher seasonal temperatures are less pronounced in this part of world where global warming may increase the length of the growing period and render suitable condition for Sunflower growth and development.

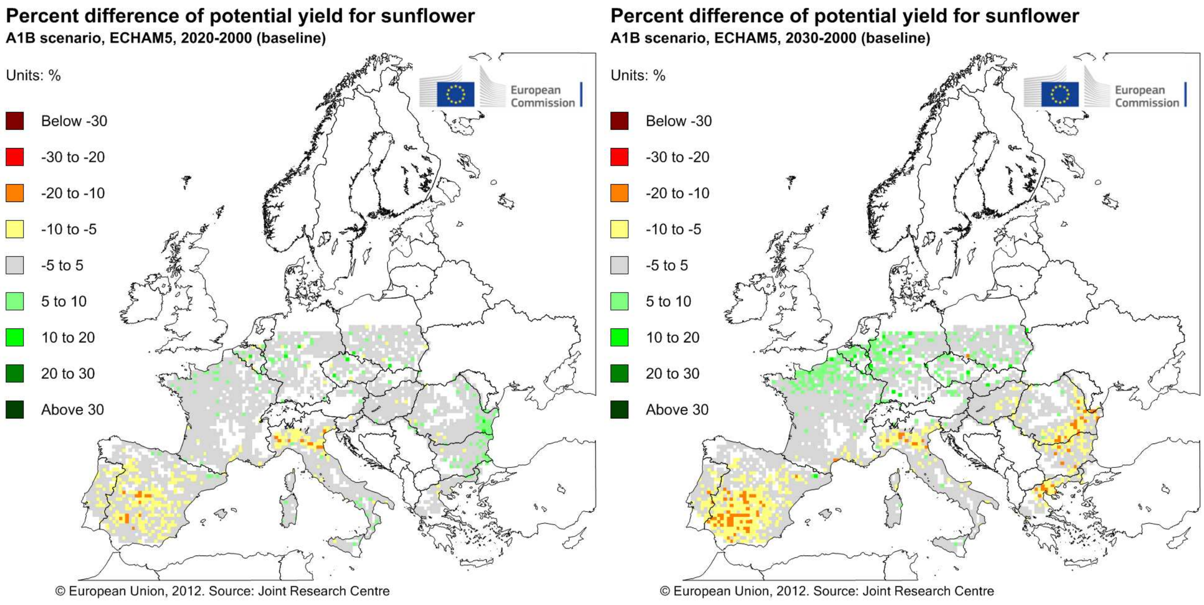


Figure 77. Percent change in simulated potential yield for rice for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Water-Limited

The simulation result in 2020 time window shows decline in sunflower yield concentrated on Spain, Italy, Romania and Bulgaria (in general area on Southern latitude) which get more pronounced by 2030 time horizon. The assertion could be higher evapotranspiration coupled with less rainfall compared to baseline period (refer weather maps).

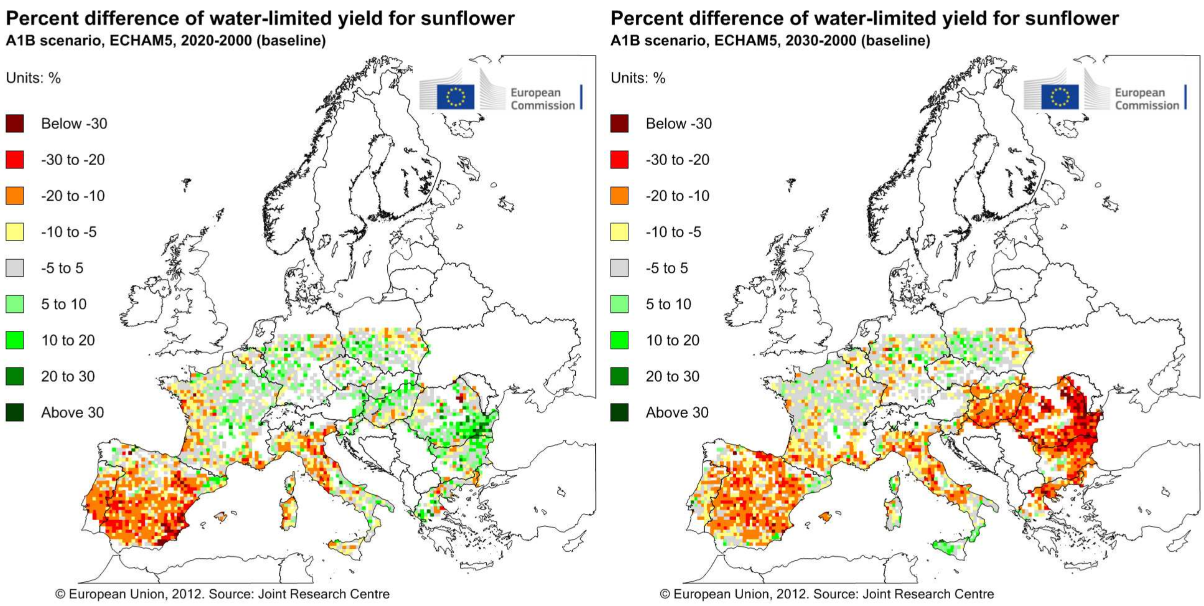


Figure 78. Percent change in simulated water-limited yield for sunflower for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Disease-Limited

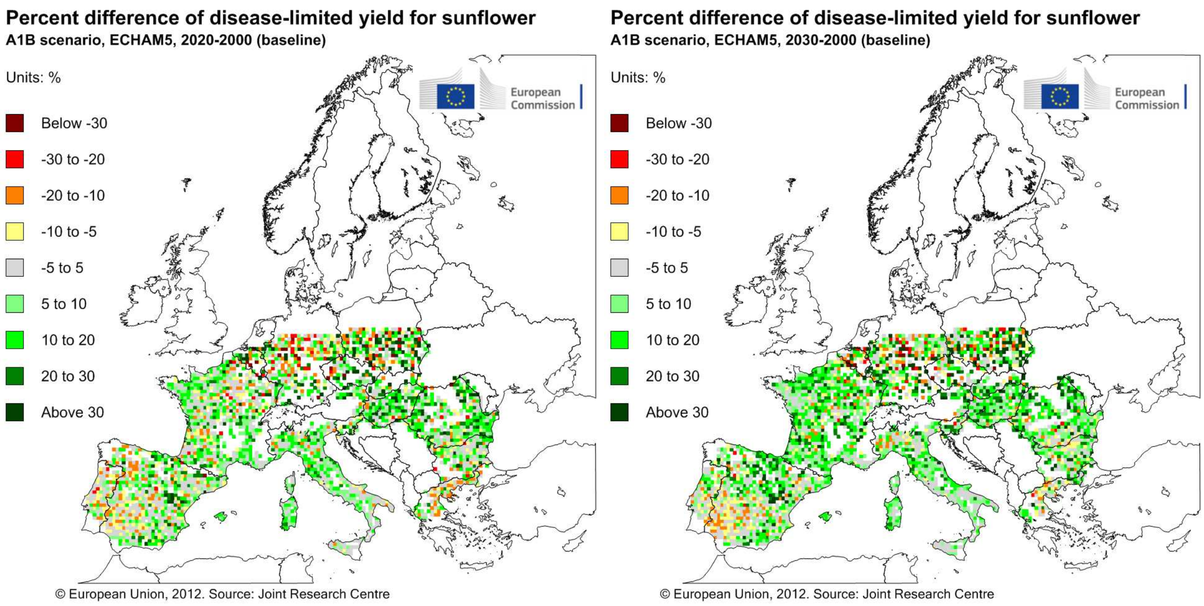
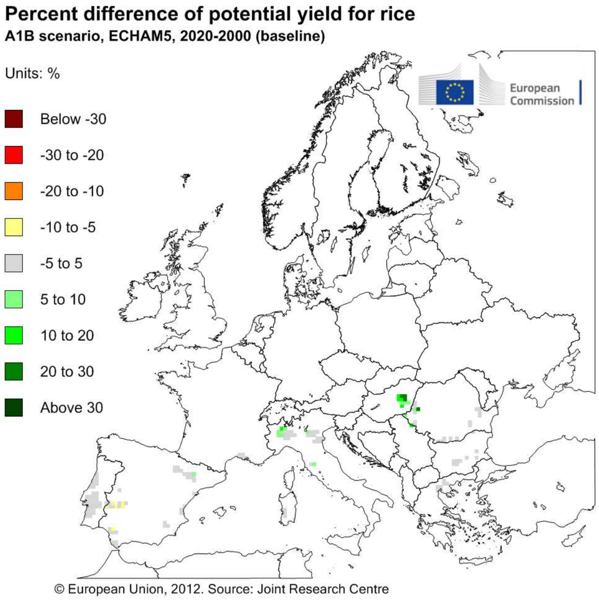


Figure 79. Percent change in simulated yield for sunflower limited by disease (*Alternaria helianthi*) for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Rice

Potential

Improvements in yield can be expected in parts of North-Western Italy, Hungary, Romania and Bulgaria whereas yield estimates remain unchanged in rest of the simulated area with some decline of 5-10% in parts of Southern Spain, Bulgaria and Greece. Generally, the increased yield can be explained by the fact that current temperature conditions are still below the optimal and increasing temperatures in future climate scenarios would provide better growing conditions whereas decline concentrated on the Southern latitude in the mentioned countries could be a result of water stress conditions which could arise by the increased temperature by 1-2 degree Celsius along with less precipitation by 15-50 mm comparing to baseline.



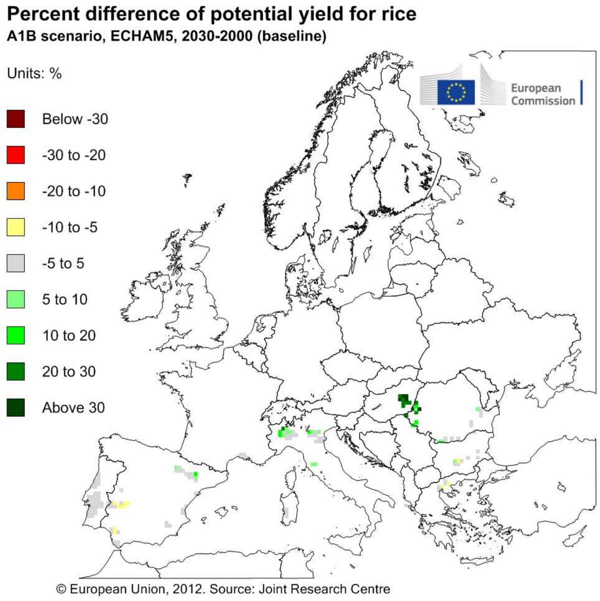
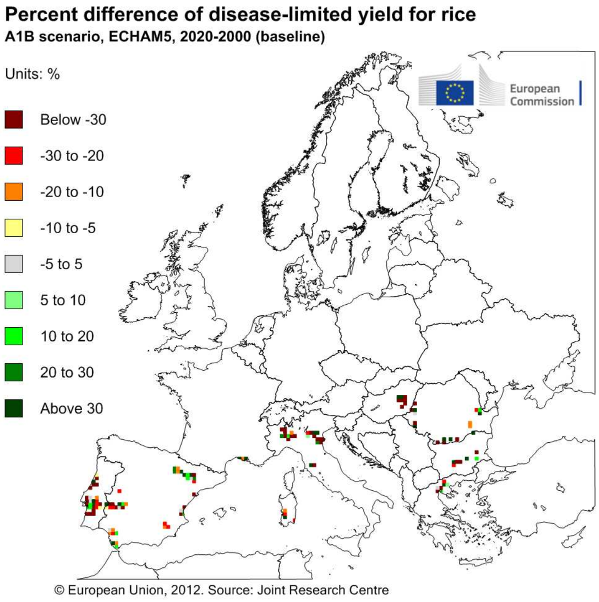


Figure 80. Percent change in simulated potential yield for rice for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

Disease-Limited



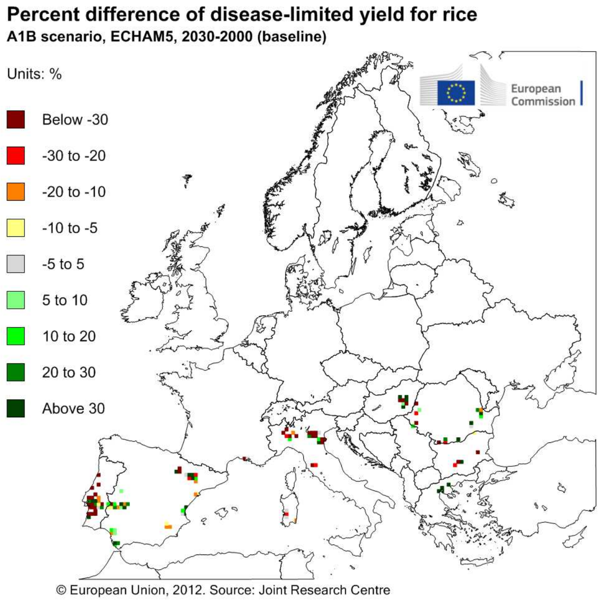


Figure 81. Percent change in simulated yield for rice limited by disease (*Pyricularia oryzae*) for 2020 (left) and 2030 (right) using the 'cold' (ECHAM5) realization of scenario A1B. No adaptation strategies are considered.

5. Spatial characterisation of EU region vulnerability

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5.1. Introduction

The two types of simulation analyses presented so far in previous chapters have shown either direct or indirect indices of probable changes in agriculture through change maps of yield. However, predicted changes in yield due to climate may be of little significance, if there is no or few presence of that crop in the modelled area.
For that reason, the results developed in previous steps must be analysed in respect of the pattern of farming, at the NUTS2 level as required for in this study. This approach has been prototyped using three such datasets:

1. A quantitative crop mask based upon the same grid as used in WP2 was used to provide preliminary estimates for the share of agriculture affected, by crop. This crop mask - which provides an estimate of the area cropped in each 25x25km grid cell across the EU27 - can thereby be used to compute absolute changes in production at cell level;
2. A five class NUTS2 level farm typology has been derived from the SEAMLESS project to provide estimates on farming systems vulnerability across EU27;
3. A more detailed NUTS2 farm level typology has been derived from the CAPRI FARM database; due to time constraint of the project, these data are used only for a limited number of Member States to show how more detailed analysis at farming system level can be carried out.

The objectives of this work package are:

- To estimate production changes at NUTS2 level based on simulated yields of WP2;
- To present the results at nation scale;
- To identify NUTS2 regions were climate changes could have a significant impact on some crops and farming systems.

WP4 takes as input the yield change estimates derived in WP2, and proceeds to determine in a partially quantitative manner, broad estimates of vulnerability by establishing the impact of the yield changes on farms types, using a simplified typology. It does this by:

- Defining, on a country-level, baseline production levels by comparing the WP2 yield outputs with E-STAT data for the baseline timeframe;
- Deriving a grid of Production change (cf. the baseline) using the Agri4Cast ASEMARS raster grid; this grid (also 25x25km^2) is a spatially disaggregated raster layer, estimating areas put down to the major crop types in the EU27. It thereby permits the calculation of a surrogate for "absolute" production change.
- Aggregation to NUTS2 level;
- Identifying NUTS2 regions affected by statistically significant variations in production and highlighting their farm typology derived from SEAMLESS (5 classes of farm type); this analysis is made for results from WP2 of both water-limited yield, and potential yield. Output from WP2 of disease-limited production is also used as ancillary information. Both map and tabular data are presented for results of the water-limited scenario (except for rice). The analysis is repeated for both “warm” and “cold” scenarios;
- Only for some countries with significant variations, example of possible more detailed analysis is carried out, by identifying the farming systems that will be affected by production variation using a farm typology derived from CAPRI-FARM (farm specialisation, farm size); tabular data are produced.

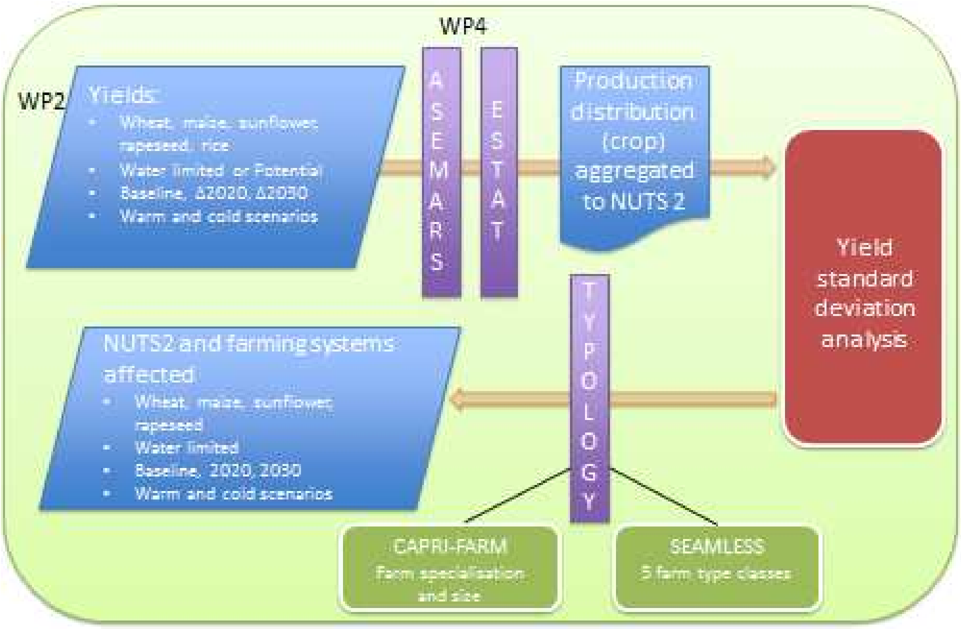


Figure 82. Overview of the method applied in work package 4.

Methodological steps and assumptions

In order to produce consistent and significant results for this work package, it has been necessary to make some assumptions and to do some works of data normalization of outputs of WP2. This is summarized hereafter.

Normalization of yield estimates

WP2 data are not expected to be able to be used for producing direct estimates of production but to give relative change to existing production estimates. Indeed, WP2 outputs are surrogates or indicators of yield (change), rather than absolute yield estimates.
Furthermore, assessing the importance of climate change impact - vulnerability - requires not just the localisation of relative yield changes, but also the analysis of the impact of the change. For example, and for a given crop, a big decrease in yield in a low intensity production zone will have significantly less importance than a moderate change in yield in a high intensity production zone. For this reason, yields must be assessed in conjunction with the production (for a given crop) in a given zone.
No dataset exists which gives a suitable baseline for production, with respect to the downscaled (raster) grid used for the modelling in AVEMAC. Thus, the project has used the ASEMARS data layer, which gives an estimate of cropped area (derived from ESTAT statistics) at raster level. Yield estimates can therefore be computed at raster level, and then aggregated to NUTS2 level to help overcome some of the spatial and statistical variability of the data. However, normalization is best applied at raster level, to ensure that the spatial resolution available in WP2 is fully utilized. Indeed, AVEMAC requires reporting at NUTS2 administrative units, so the aggregation of the raster data to this level is appropriate, and requires no downscaling from existing production statistics (which can be derived for the baseline from ESTAT data). To achieve this, ESTAT yield data need to be rasterised (but not upscaled) from the current NUTS2 reporting.
This normalisation step is applied using the following workflow per crop:

- ESTAT yield data are extracted at NUTS2 level for the baseline period (1993-2007) (EstatYldBase);
- EstatYldBase are converted to raster. Each raster cell is attributed the corresponding NUTS2 EstatYldBase value, or proportion thereof;
- AVEMAC yield raster data for the baseline are divided by with the EstatYldBase data layer; the output is a per-raster cell ratio for normalising AVEMAC yields to ESTAT baseline yields (NormBase);
- Raster cells with an ASEMARS area value of less than 1% of the cell area (i.e. 625ha) are set to null;
- A surrogate production estimate is calculated on the raster grid for baseline, 2020 and 2030 dates using the AVEMAC yield data, ASEMARS area data, normalised by the NormBase layer;
- Difference maps (Δ2020, Δ2030) of production are generated on the raster layer, showing change in production in tonnes per raster cell;
- The difference layer is aggregated to sum changes in production at NUTS2 level;
- Tables of statistics are generated to show the NUTS2 units with the most important changes in production; these identified units are then cross checked with SEAMLESS and CAPRI-FARM layers to give qualitative indicators of the farming types likely to be affected.

Normalization of yield standard deviations

WP2 also produces standard deviation of indicator of yields. They are useful for testing the significance of the variations between the baseline, 2020 and 2030. In order to remain on the same scale, the same normalization procedure was applied on the AVEMAC standard deviation, per crop. The resulting values are thus produced on the same ASEMARS raster cells.
As the normalized yield estimations are aggregated to the NUTS2 level, the result is a weighted sum. Indeed, for each crop and each NUTS2 region, the normalized yield estimations of the ASEMARS grid cells that share a surface with the given NUTS2 region are multiplied by the share of surface.
The standard deviation of the normalized yield estimations at the NUTS2 level can thus be computed as the standard deviation of a weighted sum. In absence of clear information about the correlation between the normalized yield estimations, the independence can be assumed. Consequently, the standard deviation of the weighted sum is the square root of a weighted sum of the corresponding variances, i.e.

$$\mathbb{V}ar\left(\sum_{i\in I} W_i X_i\right) = \sum_{i\in I} W_i^2 \mathbb{V}ar(X_i) = \sum_{i\in I} W_i^2 S_i^2$$

where I is the set of ASEMARS raster cells belonging to the NUTS2 region, W_i is the percentage of surface of the ASEMARS grid cell in the NUTS2, X_i is the corresponding normalized yield estimation and S_i S_i is the corresponding normalized yield standard deviation.
It is worth noting that, for a few ASEMARS raster cells, the AVEMAC yield standard deviations were not available. In order to circumvent this issue, the following assumption has been applied:

- The formula above has been applied on the available standard deviations;
- The result of this formula was normalized by multiplying the ratio between (i) the number of ASEMARS grid cells that have been used in the normalization of the yield estimations and (ii) the number of available standard deviations.

For instance, should there be 10 ASEMARS grid cells but only 7 available standard deviations, the coefficient of normalization for the variance of the corresponding NUTS2 region is 10/7.

Testing the statistical significance of the variations between the baseline, 2020 and 2030

In order to test the significance of the variations between the baseline, 2020 and 2030, a statistical test was designed based on both the normalized yield estimations and the normalized yield standard deviations both aggregated at the NUTS2 level.
For each crop, a first screening was applied on the NUTS2 regions in order to reject regions where deviation between ESTAT and AVEMAC estimates are too high and where its production is negligible at national level. Thus NUTS2 regions have been rejected for a considered crop if:

- The relative difference between the ESTAT production and the AVEMAC normalized yield estimate at the baseline is more than 10%;

and

- The ESTAT production of NUTS2 region is less than 5% of the total production of the country.

For NUTS2 regions that passed the screening, we took the normalized yield estimations M_b at the baseline, M_{2020} at 2020 and M_{2030} at 2030 and the normalized yield standard deviations S_b at the baseline, S_{2020} at 2020 and S_{2030} at 2030. The statistics of the test were:

$$T_1 = \frac{M_{2020} - M_b}{\sqrt{S_{2020}^2 + S_b^2}} \text{ and } T_2 = \frac{M_{2030} - M_b}{\sqrt{S_{2030}^2 + S_b^2}}$$

We then compared these values with the quantiles of the standardized normal distribution. The decisions of the test for both years were as followed :

- Should the value be higher than 1.96, the variation is declared significantly positive (marked as 1 in the tables showing the significant production variations in NUTS2);
- Should the value be lower than -1.96, the variation is declared significantly negative (marked as -1 in the tables showing the significant production variations in NUTS2);
- Otherwise, the variation is declared not significantly different (marked as 0 in the tables).

These results for each crop are presented in maps with seamless classes.

Some assumptions worth to note

Firstly, yield change estimates provided by WP2 refer, per crop, to one abstraction of the production systems contributing to define production for the relevant unit area. Such abstraction may represent the under laying area with a difference approximation, hence making the transformation to production at NUTS2 level subject to a variable bias.
Secondly, yield estimates are related to water-limited production, not considering other management factors, which may also impact the productions used to build statistics, assuming that

statistics are close to the production level water limited, and that the difference between the two is not influenced by other factors, includes some bias across regions.
These two points, which in any case do not include the degree of representativeness of statistics per region, suggest looking at results as trends rather than focusing on absolute estimates per area.
Finally, results must be interpreted as potential vulnerability since possible adaptation actions by farmers is not simulated.

Analysing changes according to SEAMLESS classification

The results coming from the previous steps (percentage variations of production in 2020 and 2030 and statistical significance of these variations for data based on water limited, except for rice) are analysed using the NUTS2 regions SEAMLESS farming systems .
SEAMLESS project was chosen as it develops a typology of the regions of EU that captures the huge variety of farming systems within the EU and provides a simple and uniform context to assess changes in agricultural and environmental policies. For further details on SEAMLESS project, please refer to: Andersen, (2010).
SEAMLESS derived classification is done in two steps: firstly the regions are typified based on cluster analysis for each of the three dimensions of the farm typology: farm size, intensity and specialisation/land use. Secondly, the three dimensions are combined into one typology of agricultural regions including all combinations of the three dimensions.
Thus, each NUTS2 region in the EU (except Bulgaria and Romania whose classification has not been finalised yet) has been assigned with one of the following classes:

A. Regions dominated by arable/cereal and mixed farming systems (99 regions);
B. Regions dominated by permanent crops and arable/specialised crops farming systems (29 regions);
C. Regions dominated by beef and dairy cattle systems with permanent grassland (24 regions);
D. Regions dominated by dairy farms (60 regions);
E. Regions dominated by sheep and goats farms (11 regions).

The results of the analysis of the vulnerability of the regions classified accordingly to SEAMLESS clusters are represented in maps for each crop ("warm" and "cold" scenarios), except rice. Some tables, but not all for all countries, are presented in the report to support the discussion of results. Tables for all NUT2 regions are available at: http://mars.jrc.ec.europa.eu/mars/Projects/AVEMAC/

Example of possible more detailed analysis of farming systems affected by changes (use of CAPRI data)

In the present AVEMAC study, it was decided to present a possible methodology that could be used to carry out a comprehensive analysis for the whole EU27 with a higher degree of detail at farming system level. For this scope CAPRI database is used with classification for farm type by specialisation and farm size (Gocht et al., 2011). Due to time constraint, the analysis was limited to some NUTS2 regions affected in 2030 (according to the result of the simulation) by a high decrease in production

The farm type specialisation classes and the farm size classes used are respectively listed in Table 2. and Table 3.
The results of this analysis are presented in tables that show the farming types possibly affected by a significant decrease of production in the concerned regions.

Table 2. Farm type specialization classes

Farm type	Specialization Class
1	Specialist cereals, oilseed and protein crops (FT 13) all ESU '
2	General field cropping (FT 14) + Mixed cropping (FT 60) all ESU '
3	Specialist dairying (FT 41) all ESU '
4	Specialist cattle-rearing and fattening (FT 42) + Cattle-dairying, rearing and fattening combined (FT 43) all ESU '
5	Sheep, goats and other grazing livestock (FT 44) all ESU '
6	Specialist granivores (FT 50) all ESU '
7	Mixed livestock holdings (FT 7) all ESU '
8	Mixed crops-livestock (FT 8) all ESU '
9	Specialist vineyards (FT 31) all ESU '
10	Specialist fruit and citrus fruit (FT 32) all ESU '
11	Specialist olives (FT 33) all ESU '
12	Various permanent crops combined (FT 34) all ESU '
13	Specialist horticulture (FT 20) all ESU '
99	Non-classifiable holdings all ESU ' - Residual farm

Table 3. Farm size classes

Class No.	Farm size
6	Smaller than 16 ESU -L16
7	Between 16 ESU and 100 ESU - GT16L100
8	Greater than 100 ESU - GT100
9	Non-classifiable holdings all ESU ' - Residual farm

* The economic size of farms is expressed in terms of European Size Units (ESU).

** The value of one ESU is defined as a fixed number of EUR/ECU of Farm Gross Margin.

*** Value of 1 ESU = 1200 EUR

5.2.Regions and farm typology vulnerability by crop type

Maize

For grain maize the analysis for the "warm scenario" does not show in the whole EU production important variations from the baseline to 2020, with the exception of two Romanian regions that contribute to 35% of the maize production in that country (i.e. 3,3 million tons) where a slightly decrease in production can be recorded (around -6%).
For what concerns the estimate for 2030, a decrease of about 9%, at EU level, is observed in the production of grain maize in comparison to the 2000 baseline. The decrease affects 36 NUTS2 regions with a reduction of production appraised as statistically significant.

These regions are located mainly in the most important countries for grain maize production (FR, RO, IT and HU); about 75% of them (27 out of 36) are regions where cereal and mixed farming are the most important farming systems. One has to note that some regions dominated by beef and dairy systems will also be affected. When these farming systems imply the cultivation of grain maize, a more difficult capability of adaptation can be foreseen for these farms. In NUTS2 regions where the production of grain maize has been rather stable during the baseline period, as in France, a decrease of -6% is already considered as significant (table 6). The vulnerability is more important in maize more productive regions in Romania and Italy (around 15% decrease) as well as in Hungary (10%).

A decrease of production is also expected in the Iberian Peninsula, affecting regions with different predominant farming systems: cereal and mixed farming, permanent crop and arable/specialized crop systems and a diverse pattern of farming systems with a relatively high share of dairy farms. The reduction is calculated as slightly exceeding 10%, with an absolute value more important for Spanish regions (table 7) where maize production is higher than in Portuguese ones.

The analysis for the "cold scenario" highlights an almost opposite situation. The overall production in the EU27 is expected to increase both in 2020 and 2030 compared to the baseline. In the 2020 scenario, among countries with biggest production, different regions in Italy, Spain and Romania may record a significant increase in the production; Italian and Spanish important maize production regions show an increase estimated around +15-20%. Regions affected by changes are predominantly arable/cereal and mixed farming systems or permanent crops and arable/specialised crops. Also many Greek NUTS2 regions should be affected by a significant increase in production that at national level should almost double, but this value may be biased by the high difference in the production data between ESTAT and AVEMAC baselines. In France the production seems to remain stable and no region is expected with a significant variation.

The scenario for 2030 does not show major differences from the one in 2020. There is only a slight increase of production. In this general frame of increase, a couple of regions in Romania with an important contribution to the national production may be affected by a significant decrease that anyway should be less than 10%.
The only region where the analysis for both 2020 and 2030 scenarios highlights a possible significant decrease of production is Castilla y Leon, where a decrease of 5% is expected.

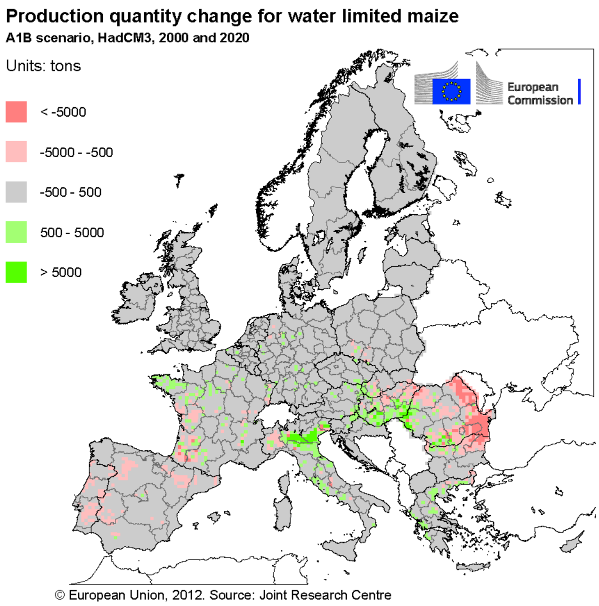
Generally the cold scenario seems to anticipate significant variations already in 2020 while with the warm scenario significant changes in production are expected only in 2030.

Table 4. Overview table for EU Member States with production figures for grain maize: water limited, normalised, tons '000, warm scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	1.755,62	1.552,69	1.571,30	1.466,83	-12%	3%	1%	-6%
BE	416,71	414,91	417,16	425,08	0%	1%	1%	2%
BG	313,11	422,93	405,19	359,35	35%	1%	-4%	-15%
CZ	338,48	297,40	301,66	279,93	-12%	1%	1%	-6%
DE	2.940,97	2.764,33	2.783,55	2.726,02	-6%	5%	1%	-1%
ES	3.767,12	3.446,93	3.352,46	3.053,12	-8%	7%	-3%	-11%
FR	14.645,90	13.794,57	13.680,64	13.261,57	-6%	27%	-1%	-4%
GR	2.053,74	1.748,58	1.821,93	1.600,13	-15%	4%	4%	-8%
HU	6.459,55	6.504,85	6.561,30	5.879,62	1%	12%	1%	-10%
IT	9.665,68	9.592,05	9.920,64	8.129,34	-1%	18%	3%	-15%
PL	1.192,61	957,50	952,82	892,32	-20%	2%	0%	-7%
RO	9.349,09	9.393,46	9.110,35	8.003,41	0%	17%	-3%	-15%
SI	308,20	267,72	277,87	246,76	-13%	1%	4%	-8%
SK	722,39	822,06	821,56	739,15	14%	1%	0%	-10%
EU	**53.929,18**	**51.980,00**	**51.978,43**	**47.062,63**	**-4%**	**100%**	**0%**	**-9%**

Table 5. Overview table for EU Member States with production figures for grain maize: water limited, normalised, tons '000, cold scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	1.755,62	1.550,58	1.530,90	1.577,39	-12%	3%	-1%	2%
BE	416,71	414,57	416,11	430,18	-1%	1%	0%	4%
BG	313,11	422,87	637,47	574,72	35%	1%	51%	36%
CZ	338,48	292,24	294,08	294,30	-14%	1%	1%	1%
DE	2.940,97	2.749,61	2.767,77	2.812,55	-7%	5%	1%	2%
ES	3.767,12	3.443,93	4.492,16	4.422,72	-9%	7%	30%	28%
FR	14.645,90	13.678,59	13.689,26	13.668,90	-7%	27%	0%	0%
GR	2.053,74	1.748,40	3.425,71	3.107,78	-15%	4%	96%	78%
HU	6.459,55	6.485,23	6.528,79	6.302,02	0%	12%	1%	-3%
IT	9.665,68	9.581,41	12.129,92	11.741,31	-1%	18%	27%	23%
PL	1.192,61	948,90	963,52	974,65	-20%	2%	2%	3%
RO	9.349,09	9.324,72	10.920,92	10.003,07	0%	17%	17%	7%
SI	308,20	252,14	255,92	250,80	-18%	1%	1%	-1%
SK	722,39	819,30	819,78	805,43	13%	1%	0%	-2%
EU	**53.929,18**	**51.712,50**	**58.872,32**	**56.965,83**	**-4%**	**100%**	**14%**	**10%**



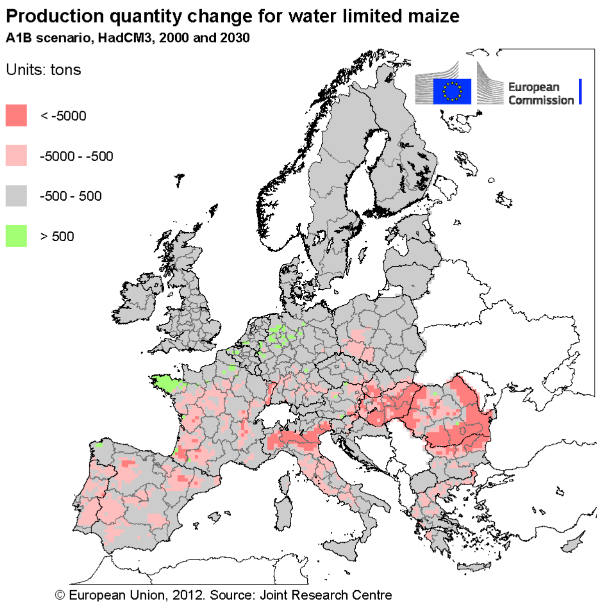


Figure 83. Change in simulated production for water-limited maize between 2000-2020 and 2000-2030. No adaptation considered. Warm scenario

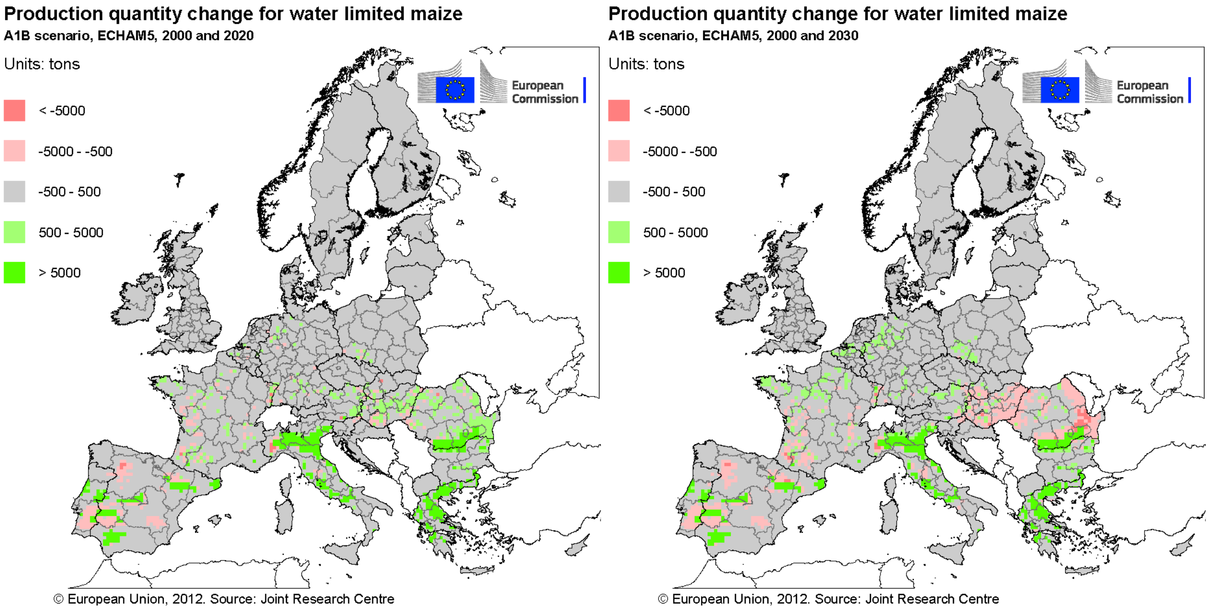


Figure 84. Change in simulated production for water-limited maize between 2000-2020 and 2000-2030. No adaptation considered. Cold scenario

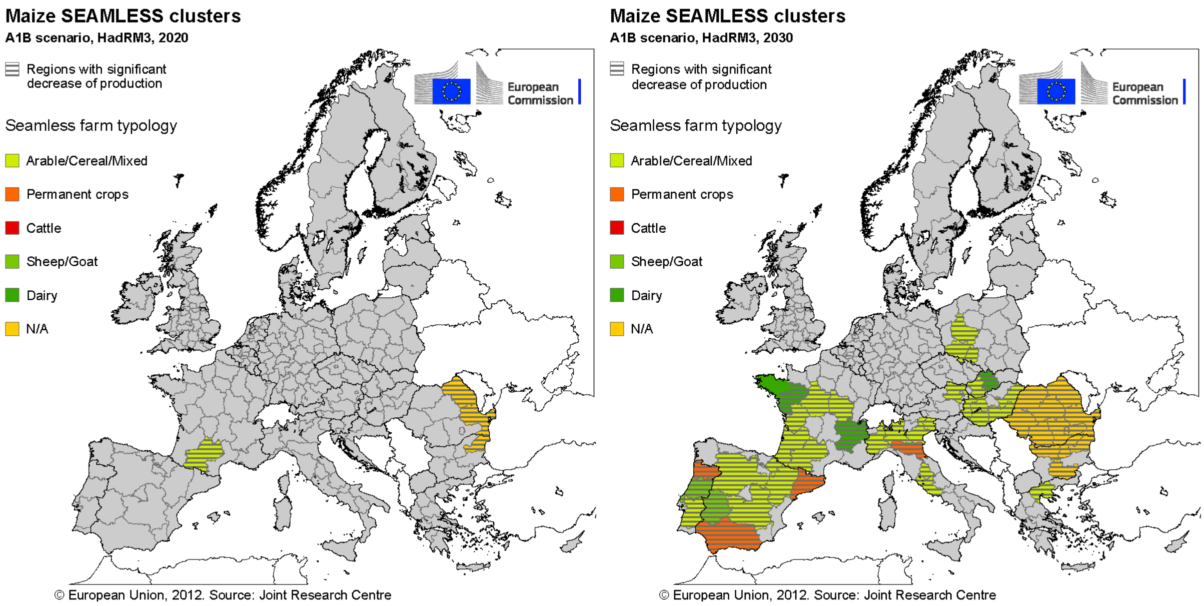


Figure 85. NUTS2 regions showing significant variation in simulated water-limited production for maize in 2000-2020 and 2000-2030, warm scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.

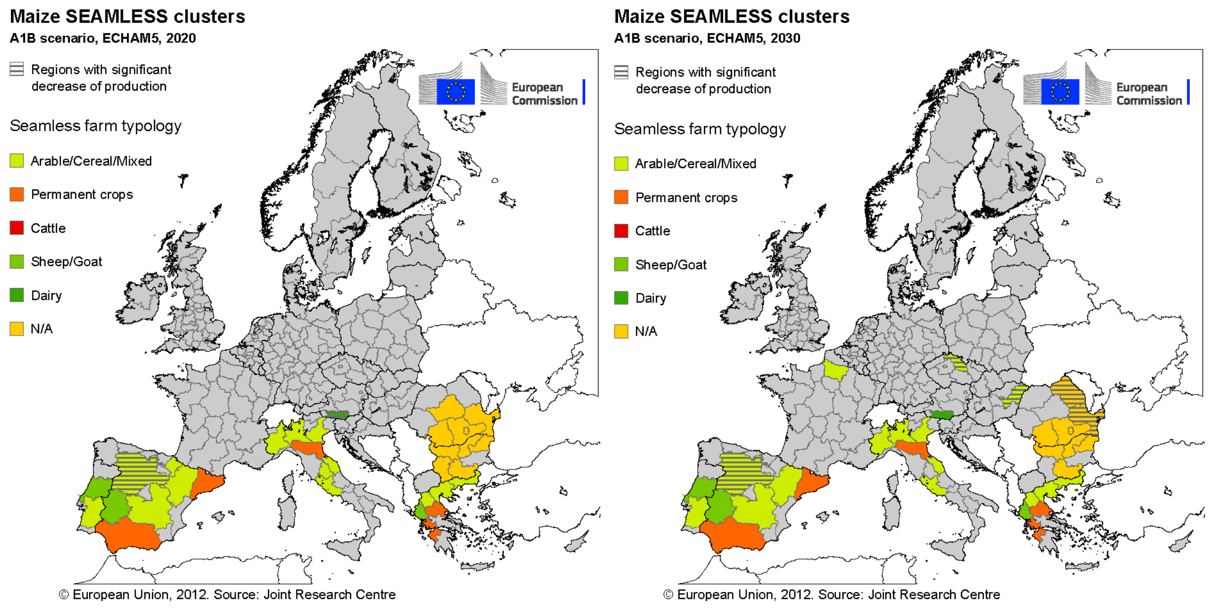


Figure 86. NUTS2 regions showing significant variation in simulated water-limited production for maize in 2000-2020 and 2000-2030, cold scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.

Table 6. Significant production variations in French NUTS2 for maize "warm" scenario, water limited, normalised, 000 tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
FR10	Ile de France	A	333,55	347,55	0%	-3%	0	0
FR21	Champagne-Ardenne	A	401,95	387,77	1%	-2%	0	0
FR22	Picardie	A	318,26	349,67	2%	1%	0	0
FR23	Haute-Normandie	A	67,87	31,62	3%	3%		
FR24	**Centre (FR)**	**A**	**1.229,67**	**1.295,67**	**1%**	**-5%**	**0**	**-1**
FR25	Basse-Normandie	D	121,41	38,46	2%	0%		
FR26	**Bourgogne**	**A**	**386,41**	**386,51**	**-1%**	**-6%**	**0**	**-1**
FR30	Nord - Pas-de-Calais	A	87,37	67,67	2%	4%		
FR41	Lorraine	D	102,55	85,73	2%	0%		
FR42	Alsace	A	1.289,91	951,19	0%	-7%	0	0
FR43	Franche-Comté	D	236,78	262,16	-1%	-6%		
FR51	**Pays de la Loire**	**D**	**1.044,27**	**967,36**	**0%**	**-3%**	**0**	**-1**
FR52	Bretagne	D	970,01	910,05	2%	4%	0	1
FR53	**Poitou-Charentes**	**A**	**1.633,45**	**1.636,64**	**-1%**	**-5%**	**0**	**-1**
FR61	**Aquitaine**	**A**	**3.080,21**	**2.503,78**	**-1%**	**-4%**	**0**	**-1**
FR62	**Midi-Pyrenees**	**A**	**1.731,99**	**2.116,60**	**-5%**	**-4%**	**-1**	**-1**
FR63	Limousin	C	48,15	58,66	0%	-3%		
FR71	**Rhone-Alpes**	**D**	**1.169,26**	**1.014,59**	**0%**	**-7%**	**0**	**-1**
FR72	Auvergne	C	297,93	301,97	0%	-5%	0	0
FR81	Languedoc-Roussillon	B	26,91	64,55	1%	-5%		
FR82	Provence-Alpes-Cote d'Azur	B	57,31	16,36	0%	-9%		
FR83	Corse	E	7,54	-	-	-		
FR91	Guadeloupe (FR)		0,02	-	-	-		
FR93	Guyane (FR)		0,01	-	-	-		
FR94	Réunion (FR)		3,11	-	-	-		
FR			**14.645,90**	**13.794,57**	**-1%**	**-4%**		

Table 7. Significant production variations in Spanish NUTS2 for maize "warm" scenario, water limited, normalised, 000 tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
ES11	Galicia	D	161,18	54,96	0%	0%		
ES12	Principado de Asturias	C	3,70	1,68	-5%	-6%		
ES13	Cantabria	C	1,39	-	-	-		
ES21	Pais Vasco	E	2,38	3,37	-3%	-5%		
ES22	**Comunidad Foral de Navarra**	**A**	**121,68**	**118,47**	**-3%**	**-8%**	**0**	**-1**
ES23	La Rioja	B	12,95	18,22	-4%	-10%		
ES24	**Aragon**	**A**	**669,29**	**691,69**	**-3%**	**-13%**	**0**	**-1**
ES30	Comunidad de Madrid	C	92,96	82,82	-2%	-16%		
ES41	**Castilla y Leon**	**A**	**950,92**	**1.098,53**	**-3%**	**-8%**	**0**	**-1**
ES42	**Castilla-la Mancha**	**A**	**513,50**	**304,87**	**-2%**	**-15%**	**0**	**-1**
ES43	**Extremadura**	**E**	**504,19**	**490,64**	**-4%**	**-16%**	**0**	**-1**
ES51	**Cataluna**	**B**	**344,46**	**296,84**	**-3%**	**-11%**	**0**	**-1**
ES52	Comunidad Valenciana	B	8,71	0,11	-2%	-13%		
ES53	Illes Balears	A	3,52	-	-	-		
ES61	**Andalucia**	**B**	**370,01**	**284,73**	**-2%**	**-11%**	**0**	**-1**
ES62	Region de Murcia	B	4,54	-	-	-		
ES70	Canarias (ES)		1,75	-	-	-		
ES			**3.767,12**	**3.446,93**	**-3%**	**-11%**		

Rice

For rice no variation considered as statistically significant is expected at NUTS2 level for both warm and cold scenarios, except in Kentriki Makedonia (GR) where the warm scenario foresees a decrease of -8% in 2030 production compared to the baseline.

Table 8. Overview table for EU Member States with ESTAT production figures for rice: potential, normalised, tons, warm scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
BG	30.600	20.514	19.257	18.270	-33%	1%	-6%	-11%
ES	713.871	669.746	653.106	646.466	-6%	27%	-2%	-3%
FR	137.043	96.192	94.060	93.718	-30%	5%	-2%	-3%
GR	179.991	119.965	114.902	110.605	-33%	7%	-4%	-8%
HU	9.123	2.890	2.946	3.198	-68%	0%	2%	11%
IT	1.385.597	1.302.067	1.304.957	1.323.654	-6%	53%	0%	2%
PT	145.413	95.997	97.561	98.169	-34%	6%	2%	2%
EU	**2.601.638**	**2.307.371**	**2.286.789**	**2.294.080**	**-11%**	**100%**	**-1%**	**-1%**

Table 9. Overview table for EU Member States with ESTAT production figures for rice: potential, normalised, tons, cold scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
BG	30.600	20.514	21.010	19.801	-33%	1%	2%	-3%
ES	713.871	669.746	649.060	644.576	-6%	27%	-3%	-4%
FR	137.043	96.192	97.625	96.072	-30%	5%	1%	0%
GR	179.991	119.965	118.804	115.584	-33%	7%	-1%	-4%
HU	9.123	2.890	3.067	3.477	-68%	0%	6%	20%
IT	1.385.597	1.302.068	1.336.782	1.360.197	-6%	53%	3%	4%
PT	145.413	95.996	95.134	95.323	-34%	6%	-1%	-1%
EU	**2.601.638**	**2.307.371**	**2.321.482**	**2.335.029**	**-11%**	**100%**	**1%**	**1%**

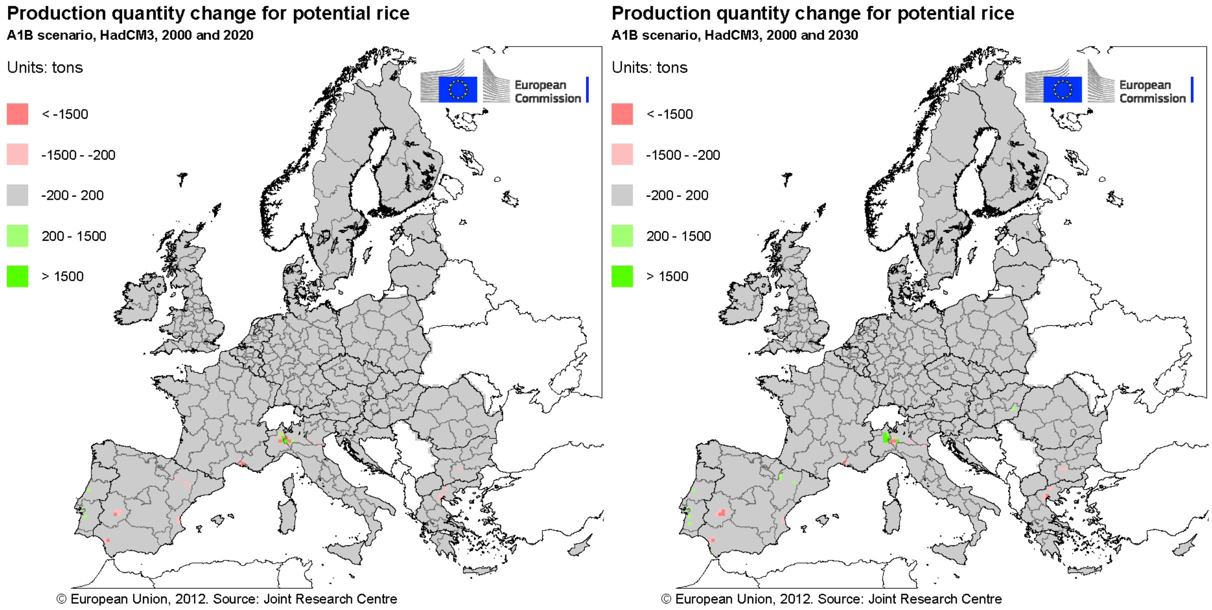


Figure 87. Change in simulated production for rice between 2000 and 2020, warm scenario. No adaptation considered.

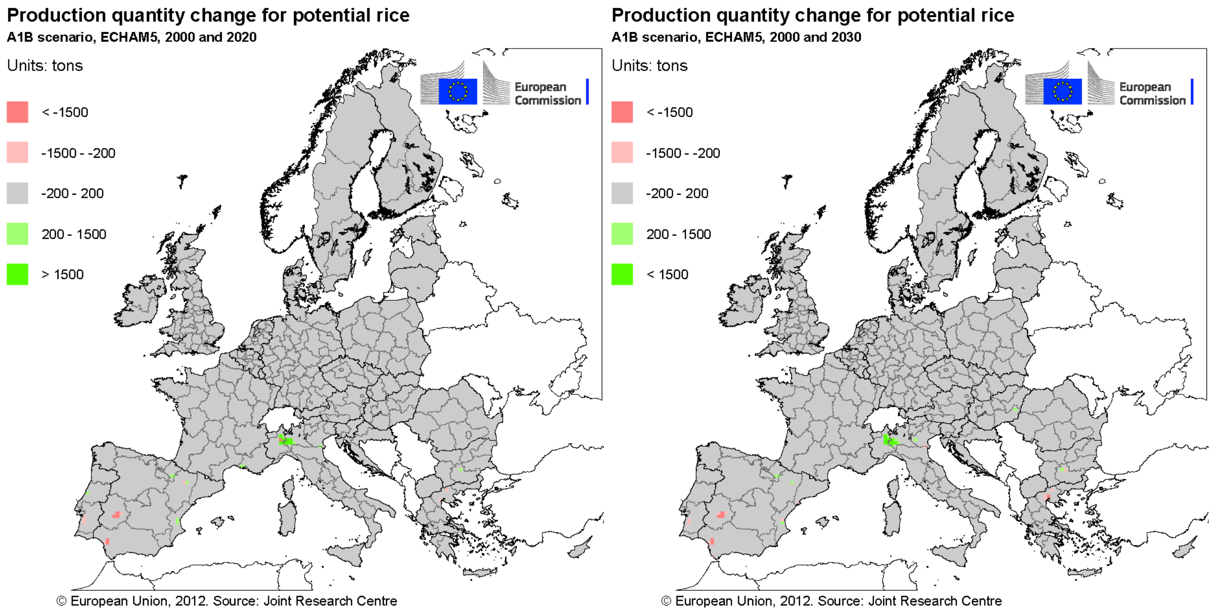


Figure 88. Change in simulated production for rice between 2000-2020 and 2000-2030, cold scenario. No adaptation considered.

Sunflower

The analysis of the “warm scenario” for sunflower shows very small variations in production in 2020 mainly concentrated in the east of the EU (some eastern areas of Bulgaria and Romania) and in the south west of the Iberian Peninsula. Anyway only three NUTS2 region seem to be impacted by a significant decrease, one each in Bulgaria (-8%), Romania (-7%), and Portugal (-6%).

The variation becomes more important and widespread when one takes into account the results of the simulation for 2030. All most important Spanish regions producing sunflower have an expected significant decrease in sunflower production of around -10%. The same happens in France, but with a smaller decrease (from -4 to -8% depending on the region).

All regions in Hungary and almost all regions in Bulgaria and Romania are also affected by a significant decrease in 2030. At country level this means -14% in Romania (with maximum of -17% in the Sud-Est region), -12% in Hungary (almost equally divided in all regions with a maximum decrease of -14% in two regions), and -13% in Bulgaria (table 10). Regions affected by sunflower significant variations are characterised by a prevalence of cereal and mixed farming systems.

The analysis for the “cold scenario” anticipates to 2020 the variations foreseen in the warm scenario in 2030 for all most important Spanish regions producing sunflower with a decrease in production of around 15% (more severe than in 2030 warm scenario). A significant decrease of production will affect all regions in Slovakia, but only one of them has an important sunflower production (where a decrease of 12% of the production is expected).

The 2030 cold scenario almost reflects the results obtained with the warm scenario at least for what concerns the identification of the NUTS2 regions where a decrease in production can be expected (in Spain, Hungary, Bulgaria and Romania). The most relevant difference is that French regions seem not be concerned by a diminution of the production in the cold scenario, except Midi-Pyrenees (-10% in cold scenario and -6% in warm scenario). In Romanian regions the decrease is much more severe in the cold scenario (around - 20-25%) than in the warm one (around -10%-13%). In Hungarian regions the cold scenario show slightly bigger decrease of production that the warm one (tables 12 and 13), while in Spanish regions the two scenarios gives more uniform results.

Table 10. Overview table for EU Member States with production figures for sunflower: water limited, normalised, tons, warm scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	64.453	36.880	37.866	34.811	-75%	1%	3%	-6%
BG	563.713	442.464	429.382	386.359	-27%	10%	-3%	-13%
CZ	56.520	51.902	53.278	49.699	-9%	1%	3%	-4%
ES	881.793	630.872	627.330	572.625	-40%	15%	-1%	-9%
FR	1.702.440	1.313.759	1.298.609	1.236.520	-30%	29%	-1%	-6%
GR	31.527	13.076	12.956	11.978	-141%	1%	-1%	-8%
HU	856.115	683.706	690.618	605.073	-25%	15%	1%	-12%
IT	364.614	258.983	271.736	243.064	-41%	6%	5%	-6%
PT	15.707	15.955	14.985	14.207	2%	0%	-6%	-11%
RO	1.098.892	1.129.162	1.096.746	971.262	3%	19%	-3%	-14%
SL	400	5	5	4	-8629%	0%	3%	-12%
SK	142.615	149.227	149.451	134.133	4%	2%	0%	-10%
EU	**5.778.790**	**4.725.991**	**4.682.962**	**4.259.735**	**-22%**	**100%**	**-1%**	**-10%**

Table 11. Overview table for EU Member States with production figures for sunflower: water limited, normalised, tons, cold scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	64.453	31.965	32.089	25.458	-102%	1%	0%	-20%
BG	563.713	442.464	455.478	355.446	-27%	10%	3%	-20%
CZ	56.520	40.700	40.706	30.791	-39%	1%	0%	-24%
ES	881.793	613.769	519.310	525.710	-44%	15%	-15%	-14%
FR	1.702.440	1.268.105	1.198.783	1.185.773	-34%	29%	-5%	-6%
GR	31.527	13.076	12.074	11.449	-141%	1%	-8%	-12%
HU	856.115	650.093	587.253	531.956	-32%	15%	-10%	-18%
IT	364.614	269.605	242.144	238.942	-35%	6%	-10%	-11%
PT	15.707	15.955	13.205	14.772	2%	0%	-17%	-7%
RO	1.098.892	1.106.839	1.162.964	830.868	1%	19%	5%	-25%
SL	400	-	-	-	-	0%	-	-
SK	142.615	136.912	109.994	114.436	-4%	2%	-20%	-16%
EU	**5.778.790**	**4.589.481**	**4.373.999**	**3.865.600**	**-26%**	**100%**	**-5%**	**-16%**

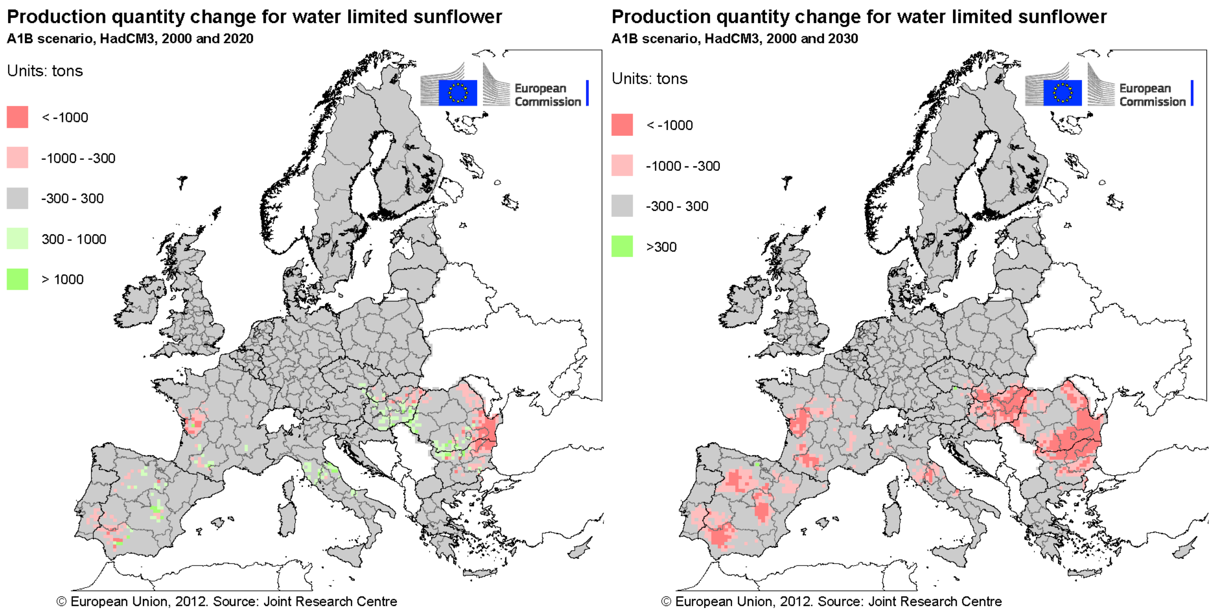


Figure 89. Change in simulated production for water-limited sunflower between 2000-2020 and 2000-2030, warm scenario. No adaptation considered.

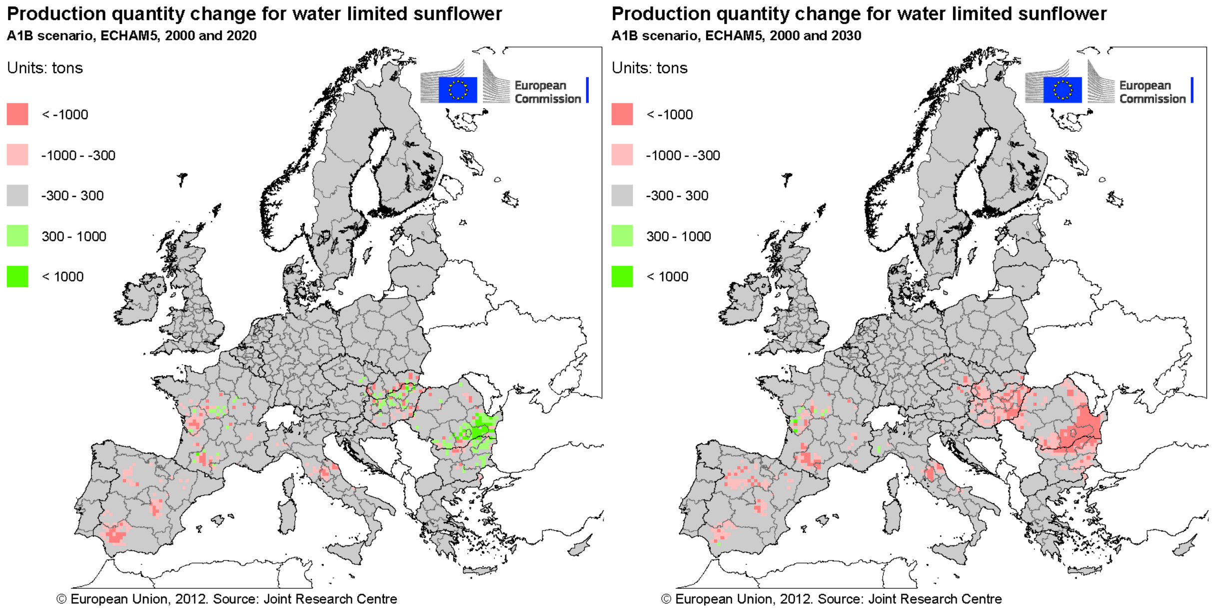
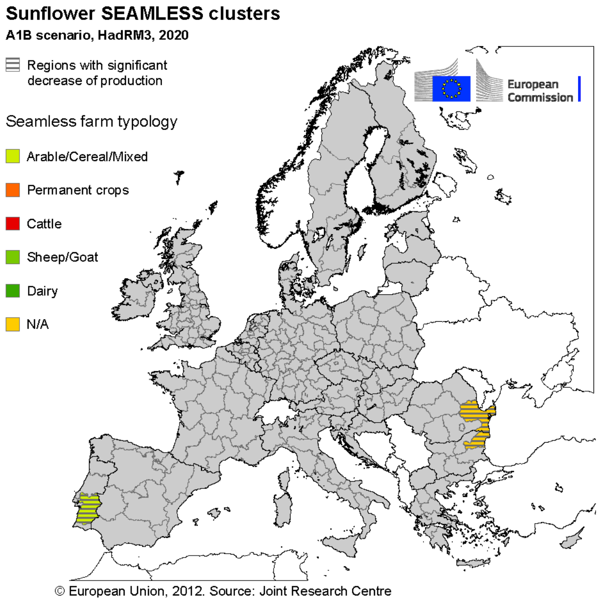


Figure 90. Change in simulated production for water-limited sunflower between 2000 and 2030 , cold scenario. No adaptation considered.



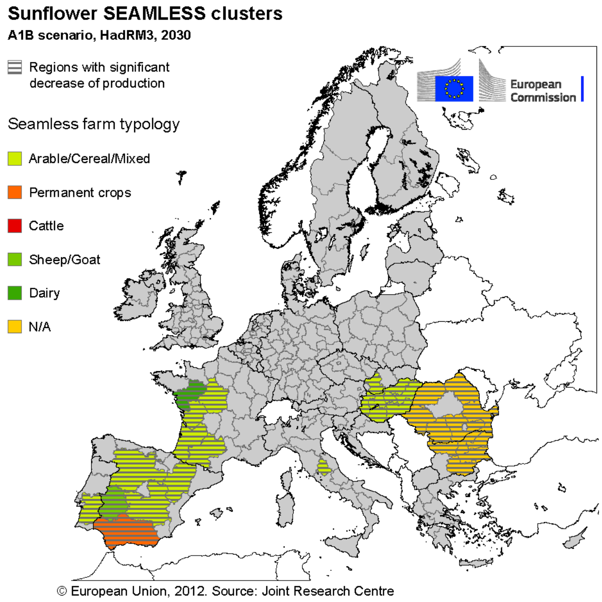
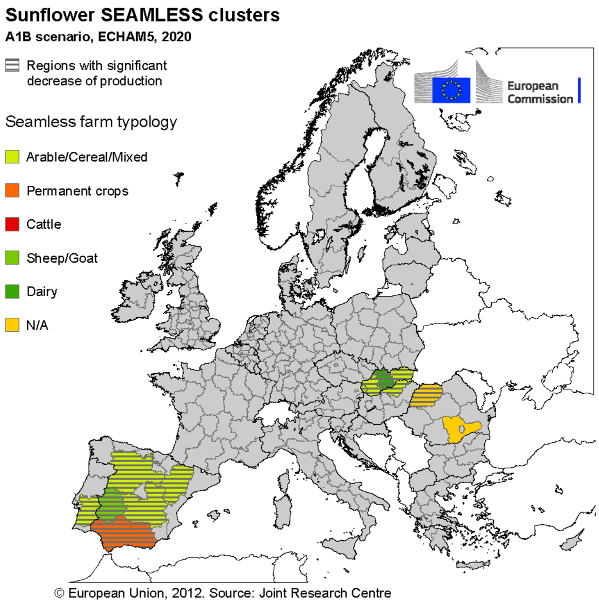


Figure 91. NUTS2 regions showing significant variation in simulated water-limited production for sunflower in 2000-2020 and 2000-2030, warm scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.



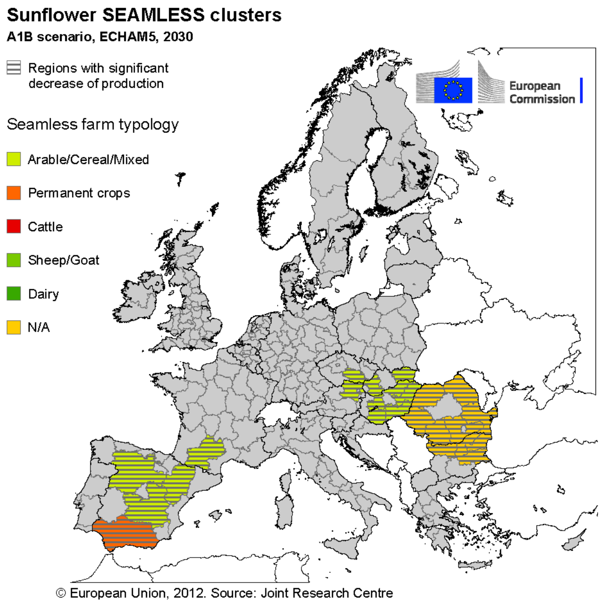


Figure 92. NUTS2 regions showing significant variation in simulated water-limited production for sunflower in 2000-2020 and 2000-2030, cold scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.

Table 12. Significant production variations in Hungarian NUTS2 for sunflower "warm" scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020-BASELINE	SIGN 2030 - BASELINE
HU10	**Kozep-Magyarorszag**	**A**	**53.646**	**48.221**	**0%**	**-12%**	**0**	**-1**
HU21	**Kozep-Dunantul**	**A**	**99.723**	**75.812**	**2%**	**-9%**	**0**	**-1**
HU22	**Nyugat-Dunantul**	**A**	**50.454**	**38.184**	**1%**	**-9%**	**0**	**-1**
HU23	**Del-Dunantul**	**A**	**97.515**	**58.405**	**5%**	**-8%**	**0**	**-1**
HU31	**Eszak-Magyarorszag**	**A**	**113.877**	**109.869**	**-2%**	**-14%**	**0**	**-1**
HU32	**Eszak-Alfold**	**A**	**217.546**	**190.874**	**-1%**	**-14%**	**0**	**-1**
HU33	**Del-Alfold**	**A**	**223.354**	**162.342**	**4%**	**-10%**	**0**	**-1**
HU			**856.115**	**683.706**	**1%**	**-12%**		

Table 13. Significant production variations in Hungarian NUTS2 for sunflower "cold" scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
HU10	Kozep-Magyarorszag	A	53.646	47.393	-3%	-11%	0	0
HU21	**Kozep-Dunantul**	**A**	**99.723**	**75.812**	**1%**	**-13%**	**0**	**-1**
HU22	Nyugat-Dunantul	A	50.454	38.184	-9%	-12%	0	0
HU23	**Del-Dunantul**	**A**	**97.515**	**56.597**	**-9%**	**-16%**	**0**	**-1**
HU31	**Eszak-Magyarorszag**	**A**	**113.877**	**104.636**	**-13%**	**-22%**	**-1**	**-1**
HU32	**Eszak-Alfold**	**A**	**217.546**	**174.399**	**-11%**	**-20%**	**0**	**-1**
HU33	**Del-Alfold**	**A**	**223.354**	**153.072**	**-14%**	**-21%**	**0**	**-1**
HU			**856.115**	**650.093**	**-10%**	**-18%**		

Wheat

For wheat production the model for the “warm scenario” highlights two different areas: a northern area including France, England, Belgium, Northern Germany, Poland and Lithuania where a decrease of wheat production is expected and a Southern area including Spain, Italy, Czech Republic, Hungary, Romania and Bulgaria where an increase of production is foreseen. The decrease in the North of Europe seems to become more severe in 2030, while the increase in the Southern countries may become less important in 2030.

After the statistical analysis on the significance of the production variation, it seems that, a part from Lithuania, no significant decrease will affect NUTS2 regions in 2020, while in2030 some regions in Northern France, Poland, Lithuania and Latvia can be affected by a decrease that can be considered as significant. Regions affected have a predominance of cereal and mixed farming systems, but in France also some regions characterized by a diverse pattern of farming systems with a relatively high share of dairy farms are impacted (table 16). Due to the hypothesis assumed for the statistical analysis in relation to the threshold of 5% of the share of production in NUTS2 regions, many Northern German regions have not been taken into account in the statistical analysis and therefore their decrease has not been highlighted as significant, even if in reality it may be. Disaggregated data on production at NUTS2 level for UK were not available and therefore the statistical analysis was not carried out.

In the Southern regions with an expected increase of production, most regions that seem to be affected by a significant increase in 2020 will have an insignificant variation in 2030 compared to the baseline. In fact, in 2030 only a few regions in Italy (table 17), Bulgaria and Spain still have a significant increase; they are characterised by a predominance of cereal and mixed farming systems and by a relatively high share of the area managed by permanent crop systems and/or by arable/specialised crop systems.

While the “warm scenario” does not foresee any significant decrease of production in 2020, the analysis for the “cold scenario” highlights different NUTS2 regions that may be affected by a significant decrease of wheat production. Most important regions for wheat production in Spain may suffer from a decline ranging from -16% to -8% (for two of them, Castilla-La Mancha and Andalusia, the warm scenario foresees an increase in production instead). For some of them the decline is confirmed in 2030 too. A decrease of around 10% is expected also for many Polish regions characterized by arable/cereal and mixed farming systems, bur some of them are not the ones that contribute the most to the wheat production in Poland. On the contrary some Regions in Northern and Western France and among them the most important ones for wheat production (Picardie and Centre) should register a statistically significant increase (from 7% to 10%).

The cold scenario for 2030 confirms a significant decrease of production in several Polish regions but not in as many regions as the warm scenario foresees (tables 18 and 19). Not expected with the warm scenario, all Romanian, northern Bulgarian and western Hungarian regions will be affected by a significant decrease of production according to the cold scenario.

For German lander the cold scenario foresees a general slight increase of production in 2020 and a decrease in 2030, but due to the small extend of the Lander, the conditions assumed excluded them from the statistical analysis and therefore these variations are not regarded as significant even if some of them may be.

Table 14. Overview table at Member State level for wheat: tons, water limited estimates, normalized, warm scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	1.355.887	1.264.008	1.465.063	1.285.565	-7%	1%	16%	2%
BE	1.653.415	1.593.277	1.485.851	1.364.659	-4%	2%	-7%	-17%
BG	2.434.886	2.281.883	2.600.638	2.441.220	-6%	2%	14%	7%
CZ	3.885.460	3.921.194	4.344.409	3.756.104	1%	4%	11%	-4%
DE	14.043.795	17.971.006	17.454.010	16.163.810	28%	13%	-3%	-11%
DK	4.660.400	3.738.210	3.698.962	3.623.743	-20%	4%	-1%	-3%
EE	119.025	72.169	74.709	71.370	-39%	0%	4%	-1%
ES	5.407.507	5.619.735	5.893.955	5.731.759	4%	5%	5%	2%
FI	557.439	76.682	88.224	97.839	-86%	1%	15%	22%
FR	34.554.567	34.384.132	34.525.020	31.515.451	0%	32%	0%	-9%
GR	2.076.591	1.847.763	2.020.360	1.917.300	-11%	2%	9%	4%
HU	4.347.215	4.247.510	4.739.527	4.250.678	-2%	4%	12%	0%
IE	730.907	698.386	642.044	626.287	-4%	1%	-8%	-12%
IT	8.490.408	7.285.996	8.873.198	8.295.003	-14%	8%	22%	12%
LT	1.052.567	965.960	911.523	848.893	-8%	1%	-6%	-14%
LU	61.250	65.664	64.912	60.054	7%	0%	-1%	-9%
LV	422.336	468.709	439.985	434.551	11%	0%	-6%	-8%
MT	9.150	0	0	0	-100%	0%		
NL	1.090.353	1.100.976	989.084	960.306	1%	1%	-10%	-15%
PL	8.693.354	9.032.190	8.947.940	7.685.642	4%	8%	-1%	-18%
PT	244.849	281.666	278.611	281.747	15%	0%	-1%	0%
RO	5.431.015	5.407.635	6.250.656	5.785.980	0%	5%	16%	7%
SE	2.045.196	1.970.627	2.056.390	1.984.363	-4%	2%	4%	1%
SI	133.000	94.121	108.287	99.577	-29%	0%	15%	5%
SK	1.560.964	1.618.953	1.791.829	1.501.143	4%	1%	11%	-8%
UK	2.457.250	2.429.786	2.258.301	2.243.444	-1%	2%	-7%	-8%
EU	**107.518.785**	**108.438.238**	**112.003.488**	**103.026.487**	**1%**	**100%**	**3%**	**-5%**

Table 15. Overview table at Member State level for wheat: tons, water limited estimates, normalized, cold scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	1.355.887	1.264.009	1.220.241	1.141.377	-7%	1%	-3%	-11%
BE	1.653.415	1.593.279	1.614.481	1.578.880	-4%	2%	1%	-1%
BG	2.434.886	2.278.399	2.343.302	1.930.530	-6%	2%	3%	-18%
CZ	3.885.460	3.903.794	3.725.509	3.565.791	0%	4%	-5%	-9%
DE	14.043.795	18.020.988	18.863.603	17.661.742	28%	13%	5%	-2%
DK	4.660.400	3.695.092	4.132.900	3.946.167	-21%	4%	12%	6%
EE	119.025	45.254	41.891	46.252	-62%	0%	-7%	2%
ES	5.407.507	5.619.735	5.034.599	5.326.664	4%	5%	-10%	-6%
FI	557.439	38.584	7.311	7.748.447	-93%	1%	-81%	100%
FR	34.554.567	34.376.066	36.467.027	34.215.177	-1%	32%	6%	0%
GR	2.076.591	1.847.763	1.826.589	1.709.534	-11%	2%	-1%	-8%
HU	4.347.215	4.247.510	4.224.575	3.904.320	-2%	4%	-1%	-9%
IE	730.907	698.386	764.314	719.564	-4%	1%	9%	3%
IT	8.490.408	7.410.594	6.816.110	7.359.821	-13%	8%	-8%	-1%
LT	1.052.567	962.788	908.015	939.697	-9%	1%	-6%	-2%
LU	61.250	65.664	63.538	62.316	7%	0%	-3%	-5%
LV	422.336	434.992	436.937	446.065	3%	0%	0%	2%
MT	9.150	0	0	0	-100%	0%		
NL	1.090.353	1.100.976	1.190.957	1.139.146	1%	1%	8%	3%
PL	8.693.354	9.038.108	8.511.811	8.145.246	4%	8%	-6%	-11%
PT	244.849	281.666	247.474	292.333	15%	0%	-12%	4%
RO	5.431.015	5.407.635	5.419.476	4.315.424	0%	5%	0%	-25%
SE	2.045.196	1.878.882	1.792.958	1.955.608	-8%	2%	-5%	4%
SI	133.000	94.121	92.503	89.977	-29%	0%	-2%	-5%
SK	1.560.964	1.614.991	1.580.500	1.464.946	3%	1%	-2%	-10%
UK	2.457.250	2.429.786	2.552.049	2.474.955	-1%	2%	5%	2%
EU	**107.518.785**	**108.349.061**	**109.878.670**	**112.179.979**	**1%**	**100%**	**1%**	**3%**

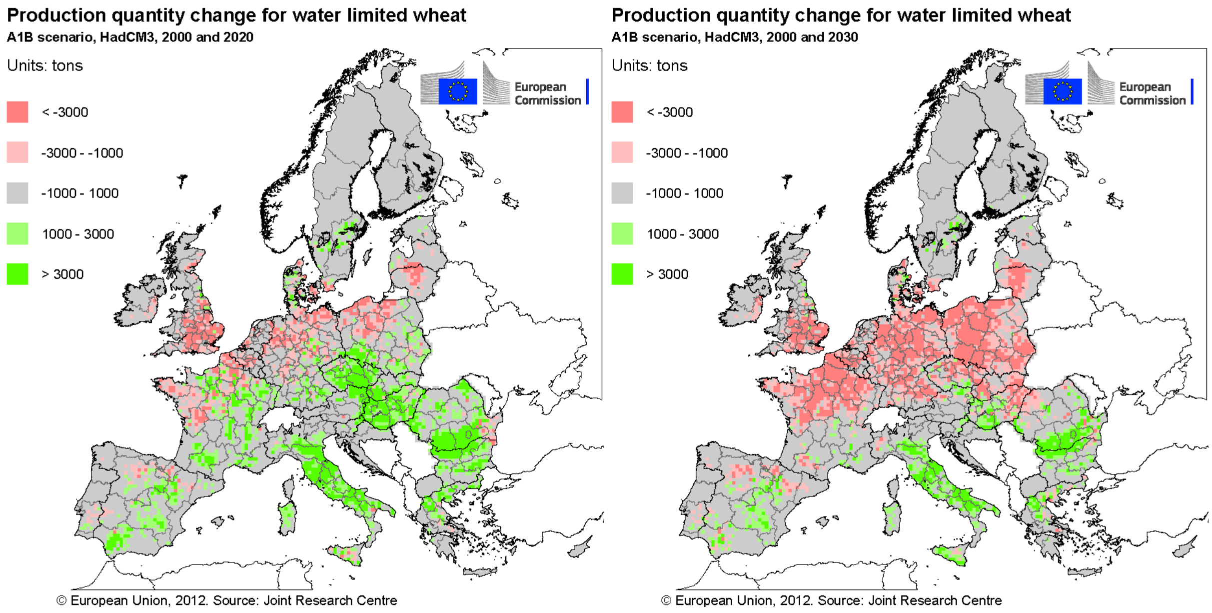


Figure 93. Change in simulated production for water-limited wheat between 2000-2020 and 2000-2030, warm scenario. No adaptation considered.

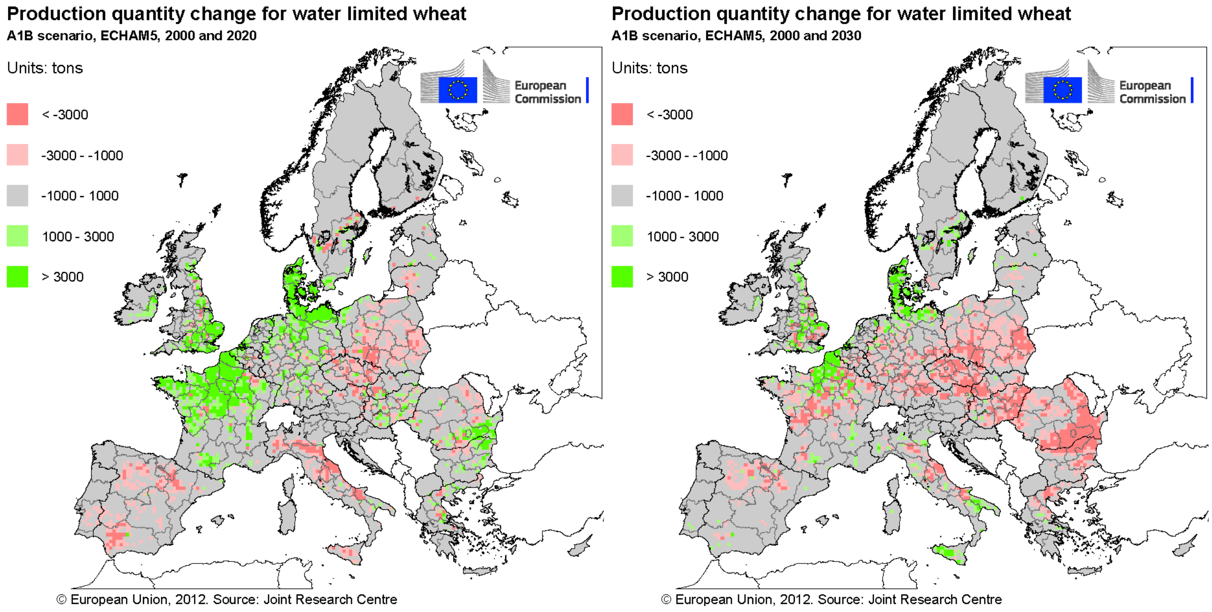


Figure 94. Change in simulated production for water-limited wheat between 2000-2020 and 2000-2030, cold scenario. No adaptation considered

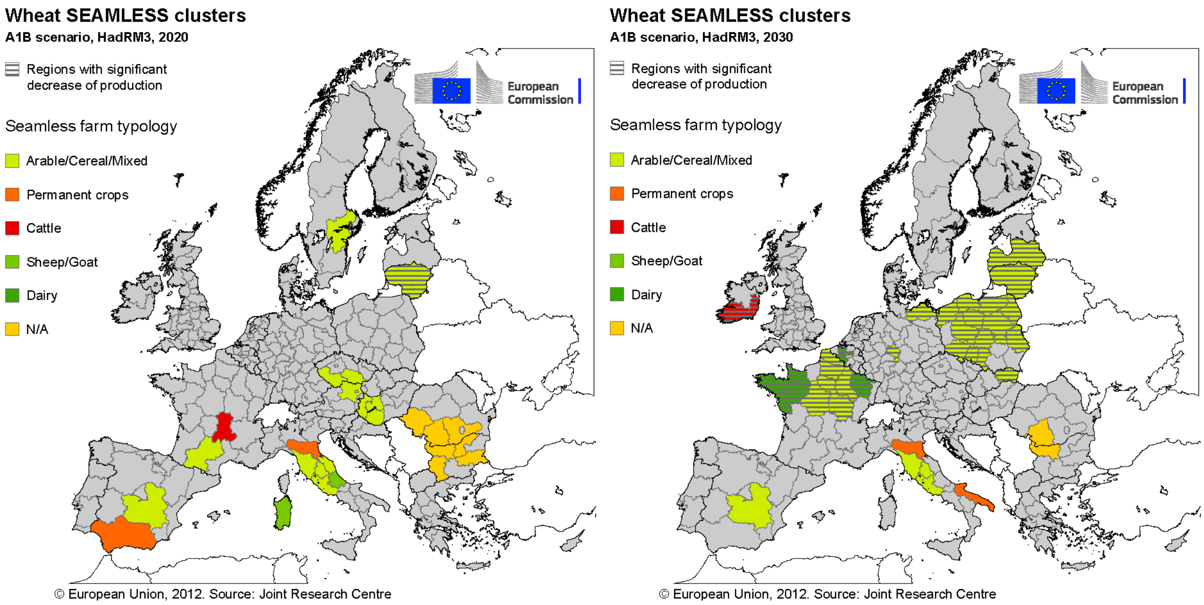


Figure 95. NUTS2 regions showing significant variation in simulated production for wheat in 2000-2020 and 2000-2030, warm scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.

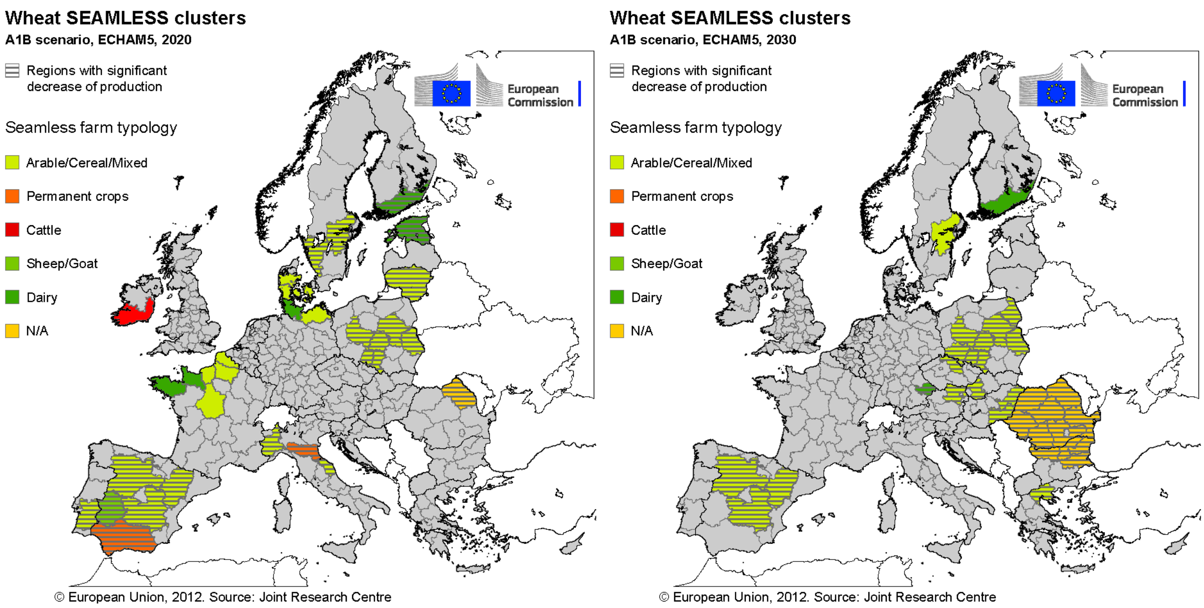


Figure 96. NUTS2 regions showing significant variation in simulated production for wheat in 2000-2020 and 2000-2030, cold scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered.

Table 16. Significant production variations in French NUTS2 for wheat "warm" scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
FR10	**Ile de France**	**A**	**1.901.153**	**1.911.596**	**-1%**	**-12%**	**0**	**-1**
FR21	**Champagne-Ardenne**	**A**	**3.145.480**	**3.233.170**	**1%**	**-11%**	**0**	**-1**
FR22	**Picardie**	**A**	**4.139.867**	**4.113.897**	**-2%**	**-13%**	**0**	**-1**
FR23	Haute-Normandie	A	1.865.327	1.723.935	1%	-10%	0	0
FR24	**Centre**	**A**	**5.358.760**	**5.415.804**	**0%**	**-11%**	**0**	**-1**
FR25	**Basse-Normandie**	**D**	**1.350.633**	**1.226.383**	**2%**	**-9%**	**0**	**-1**
FR26	**Bourgogne**	**A**	**2.122.760**	**2.216.384**	**5%**	**-8%**	**0**	**-1**
FR30	**Nord - Pas-de-Calais**	**A**	**2.214.600**	**2.049.449**	**-6%**	**-19%**	**0**	**-1**
FR41	**Lorraine**	**D**	**1.456.147**	**1.472.586**	**3%**	**-10%**	**0**	**-1**
FR42	Alsace	A	277.593	242.109	5%	-3%		
FR43	Franche-Comte	D	369.687	453.558	6%	-5%		
FR51	**Pays de la Loire**	**D**	**2.317.073**	**2.174.036**	**-3%**	**-7%**	**0**	**-1**
FR52	**Bretagne**	**D**	**1.919.287**	**1.866.237**	**-6%**	**-8%**	**0**	**-1**
FR53	Poitou-Charentes	A	2.288.960	2.265.210	-4%	-5%	0	0
FR61	Aquitaine	A	444.307	426.742	8%	-1%	0	0
FR62	Midi-Pyrenees	A	1.525.953	1.555.999	7%	-2%	1	0
FR63	Limousin	C	113.487	183.279	-2%	-7%		
FR71	Rhone-Alpes	D	630.040	637.350	11%	1%		0
FR72	Auvergne	C	611.307	666.393	15%	1%	1	0
FR81	Languedoc-Roussillon	B	288.860	314.402	10%	-3%	0	0
FR82	Provence-Alpes-Cote d'Azur	B	212.467	235.617	12%	5%		
FR83	Corse	E	820	0				
FR			**34.554.567**	**34.384.132**	**0%**	**-9%**		

Table 17. Significant production variations in Italian NUTS2 for wheat "warm" scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
ITC1	Piemonte	A	475.357	409.808	7%	-3%	0	0
ITC2	Valle d'Aosta/Vallee d'Aoste	D	29	0				
ITC3	Liguria	B	2.157	1.115	14%	7%		
ITC4	Lombardia	A	332.779	375.093	18%	7%		
ITD1	Provincia Autonoma Bolzano/Bozen	D	122	0				
ITD3	Veneto	A	27.421	317.127	16%	5%		
ITD4	Friuli-Venezia Giulia	A	1.271.364	28.172	5%	-3%	0	0
ITD5	**Emilia-Romagna**	**B**	**1.271.364**	**1.110.373**	**31%**	**13%**	**1**	**1**
ITE1	**Toscana**	**A**	**521.279**	**497.256**	**32%**	**12%**	**1**	**1**
ITE2	**Umbria**	**A**	**405.936**	**381.369**	**38%**	**13%**	**1**	**1**
ITE3	Marche	A	678.779	618.112	36%	15%	1	0
ITE4	**Lazio**	**A**	**333.571**	**360.328**	**40%**	**25%**	**1**	**1**
ITF1	Abruzzo	E	246.286	221.932	34%	15%	1	0
ITF2	Molise	A	188.750	163.958	26%	18%		
ITF3	Campania	B	294.779	208.905	26%	15%		
ITF4	**Puglia**	**B**	**957.514**	**1.120.519**	**13%**	**15%**	**0**	**1**
ITF5	Basilicata	A	430.893	396.758	10%	12%	0	0
ITF6	Calabria	B	165.800	169.723	7%	6%	0	0
ITG1	Sicilia	B	751.064	769.042	2%	8%	0	0
ITG2	Sardegna	E	135.164	136.405	18%	10%	1	0
IT			**8.490.408**	**7.285.996**	**22%**	**12%**		

Table 18. Significant production variations in Polish NUTS2 for wheat “warm” scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
PL11	**Lodzkie**	**A**	**314.862**	**338.815**	**1%**	**-21%**	**0**	**-1**
PL12	**Mazowieckie**	**A**	**484.392**	**535.876**	**1%**	**-13%**	**0**	**-1**
PL21	Malopolskie	A	355.338	315.016	4%	-8%		
PL22	**Slaskie**	**A**	**233.200**	**238.744**	**3%**	**-16%**	**0**	**-1**
PL31	**Lubelskie**	**A**	**929.000**	**898.038**	**1%**	**-12%**	**0**	**-1**
PL32	Podkarpackie	A	391.085	346.926	1%	-14%		
PL33	Swietokrzyskie	A	254.769	293.392	1%	-15%		
PL34	**Podlaskie**	**A**	**164.462**	**172.380**	**3%**	**-12%**	**0**	**-1**
PL41	**Wielkopolskie**	**A**	**883.931**	**980.953**	**-4%**	**-26%**	**0**	**-1**
PL42	**Zachodniopomorskie**	**A**	**725.138**	**802.845**	**-6%**	**-18%**	**0**	**-1**
PL43	Lubuskie	A	188.085	217.225	0%	-19%		
PL51	**Dolnoslaskie**	**A**	**1.150.338**	**1.167.619**	**8%**	**-16%**	**0**	**-1**
PL52	**Opolskie**	**A**	**707.277**	**615.424**	**4%**	**-20%**	**0**	**-1**
PL61	**Kujawsko-Pomorskie**	**A**	**755.477**	**800.275**	**-8%**	**-22%**	**0**	**-1**
PL62	**Warminsko-Mazurskie**	**A**	**565.092**	**635.816**	**-7%**	**-19%**	**0**	**-1**
PL63	**Pomorskie**	**A**	**590.908**	**672.845**	**-9%**	**-20%**	**0**	**-1**
PL			**8.693.354**	**9.032.190**	**-1%**	**-18%**		

Table 19. Significant production variations in Polish NUTS2 for wheat “cold” scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
PL11	**Lodzkie**	**A**	**314.862**	**338.815**	**-12%**	**-18%**	**-1**	**-1**
PL12	**Mazowieckie**	**A**	**484.392**	**535.876**	**-11%**	**-18%**	**-1**	**-1**
PL21	Malopolskie	A	355.338	315.016	-6%	-12%		
PL22	**Slaskie**	**A**	**233.200**	**238.744**	**-11%**	**-14%**	**-1**	**-1**
PL31	**Lubelskie**	**A**	**929.000**	**898.038**	**-9%**	**-19%**	**-1**	**-1**
PL32	Podkarpackie	A	391.085	346.926	-7%	-18%		
PL33	Swietokrzyskie	A	254.769	293.392	-9%	-15%		
PL34	**Podlaskie**	**A**	**164.462**	**172.380**	**-7%**	**-12%**	**0**	**-1**
PL41	**Wielkopolskie**	**A**	**883.931**	**980.953**	**-7%**	**-10%**	**-1**	**-1**
PL42	Zachodniopomorskie	A	725.138	810.683	6%	-2%	0	0
PL43	Lubuskie	A	188.085	217.225	-3%	-11%		
PL51	**Dolnoslaskie**	**A**	**1.150.338**	**1.165.698**	**-6%**	**-11%**	**0**	**-1**
PL52	**Opolskie**	**A**	**707.277**	**615.424**	**-13%**	**-18%**	**-1**	**-1**
PL61	Kujawsko-Pomorskie	A	755.477	800.275	-3%	-6%	0	0
PL62	Warminsko-Mazurskie	A	565.092	635.816	-5%	-5%	0	0

PL63	Pomorskie	A	590.908	672.845	0%	-3%	0	0
PL			**8.693.354**	**9.038.108**	**-6%**	**-11%**		

Rapeseed

The analysis of the "warm scenario" for rapeseed in 2020 highlights some scattered increase in central Europe that in some cases can be high in percentage (15-20%). However, the statistical analysis of this variation greatly reduces the significance of these variations only to a very few regions in Hungary, Austria and Czech Republic. All increases in production disappear in the 2030 scenario.

For the 2030 scenario, only regions in France are detected with a significant decrease. They represent the most important regions in France for rapeseed production and their significant decrease is estimated from -11% to -18% depending on the region (Table 22). Negative changes in production are also reported in some German Lander, but the statistical analysis calculates these variations as not significant.

Regions affected by rapeseed significant variations are characterized by a prevalence of cereal and mixed farming systems.

The analysis for the "cold scenario" in 2020 show some significant increase only in a few NUTS2 regions located in Northern Germany, Denmark and Poland. In the rest of Europe positive or negative variations foreseen by the model are not assessed as statistically significant.

In 2030 no significant variations are expected. French regions with significant decrease in the warm scenario, are expected to have slightly positive variations, even if not significant, in the cold scenario.

Table 20. Overview table for EU Member States with production figures for rapeseed, water limited, normalised, tons, warm scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	144.861	108.683	132.547	116.007	-25%	1%	22%	7%
BE	21.390	6.991	6.500	6.182	-67%	0%	-7%	-12%
BG	92.967	-	-	-	-100%	1%	-	-
CZ	720.420	731.514	827.713	741.562	2%	6%	13%	1%
DE	3.673.222	3.681.303	3.773.073	3.533.411	0%	29%	2%	-4%
DK	511.500	7.851	9.831	9.939	-98%	4%	25%	27%
ES	40.308	-	-	-	-100%	0%	-	-
FI	97.963	-	-	-	-100%	1%	-	-
FR	3.394.793	3.292.612	3.320.536	2.819.634	-3%	27%	1%	-14%
HU	221.477	140.782	167.404	151.673	-36%	2%	19%	8%
IE	21.333	-	-	-	-100%	0%	-	-
IT	30.153	-	-	-	-100%	0%	-	-
LT	102.687	80.420	77.184	76.291	-22%	1%	-4%	-5%
LU	10.243	9.797	10.362	9.203	-4%	0%	6%	-6%
LV	34.664	11.234	10.108	10.436	-68%	0%	-10%	-7%
NL	4.796	5.772	5.299	4.884	20%	0%	-8%	-15%
PL	1.175.646	874.462	903.105	815.915	-26%	9%	3%	-7%
SE	143.522	4.750	7.061	7.207	-97%	1%	49%	52%
SI	300	-	-	-	-100%	0%	-	-
SK	200.138	171.685	199.222	163.311	-14%	2%	16%	-5%
UK*	2.000.000	909.336	856.971	876.944	-55%	16%	-6%	-4%
EU	**12.642.383**	**10.037.190**	**10.306.914**	**9.342.598**	**-21%**	**100%**	**3%**	**-7%**

* ESTAT bline UK estimated from FAO data 2005/6/7

Table 21. Overview table for EU Member States with production figures for rapeseed, water limited, normalised, tons, cold scenario

Member State	ESTAT bline	AVEMAC bline	AVEMAC 2020	AVEMAC 2030	Δblines	%share prod	Δ20-bline	Δ30-bline
AT	144.861	108.683	106.642	100.660	-25%	1%	-2%	-7%
BE	21.390	6.991	6.419	7.108	-67%	0%	-8%	2%
BG	92.967	-	-	-	-100%	1%	-	-
CZ	720.420	694.545	676.503	678.377	-4%	6%	-3%	-2%
DE	3.673.222	3.638.154	4.065.869	3.847.711	-1%	29%	12%	6%
DK	511.500	7.810	8.889	8.110	-98%	4%	14%	4%
ES	40.308	-	-	-	-100%	0%	-	-
FI	97.963	-	-	-	-100%	1%	-	-
FR	3.394.793	3.293.749	3.420.488	3.316.232	-3%	27%	4%	1%
HU	221.477	140.782	167.404	151.673	-36%	2%	19%	8%
IE	21.333	-	-	-	-100%	0%	-	-
IT	30.153	-	-	-	-100%	0%	-	-
LT	102.687	51.282	48.382	54.218	-50%	1%	-6%	6%
LU	10.243	9.797	9.492	9.871	-4%	0%	-3%	1%
LV	34.664	5.207	5.282	5.380	-85%	0%	1%	3%
NL	4.796	5.772	5.998	6.189	20%	0%	4%	7%
PL	1.175.646	865.451	879.823	849.763	-26%	9%	2%	-2%
SE	143.522	740	758	791	-99%	1%	2%	7%
SI	300	-	-	-	-100%	0%	-	-
SK	200.138	168.048	164.714	151.939	-16%	2%	-2%	-10%
UK*	2.000.000	780.993	797.284	802.713	-61%	16%	2%	3%
EU	**12.642.383**	**9.778.003**	**10.363.948**	**9.990.735**	**-23%**	**100%**	**6%**	**2%**

* ESTAT bline UK estimated from FAO data 2005/6/7

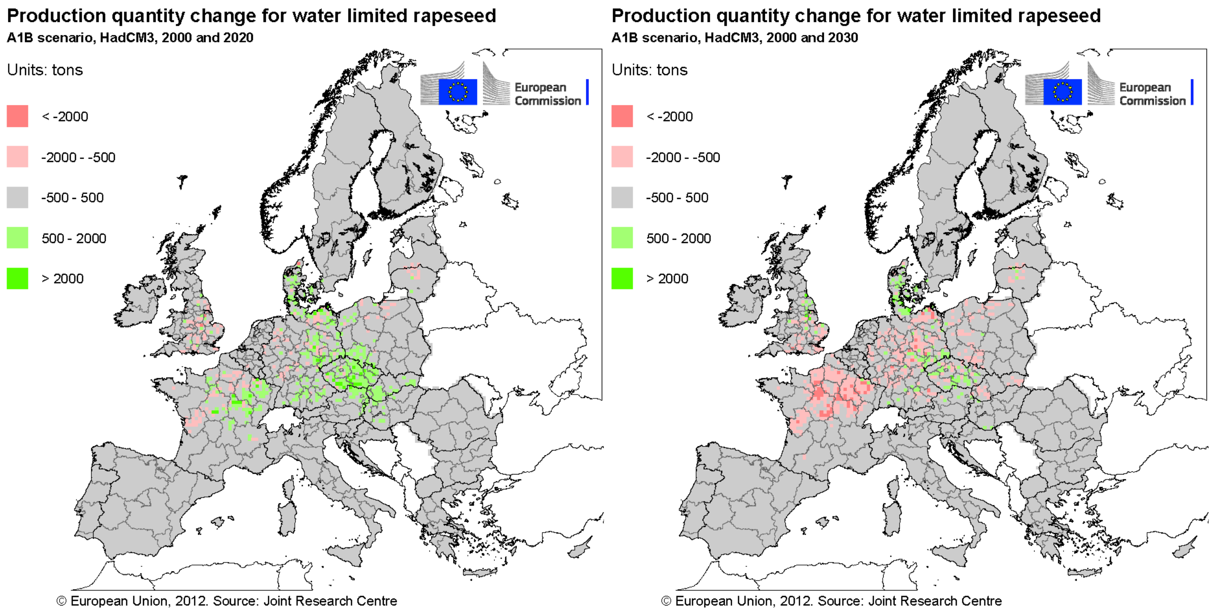


Figure 97. Change in simulated production for water-limited rapeseed between 2000-2020 and 2000-2030, warm scenario. No adaptation considered.

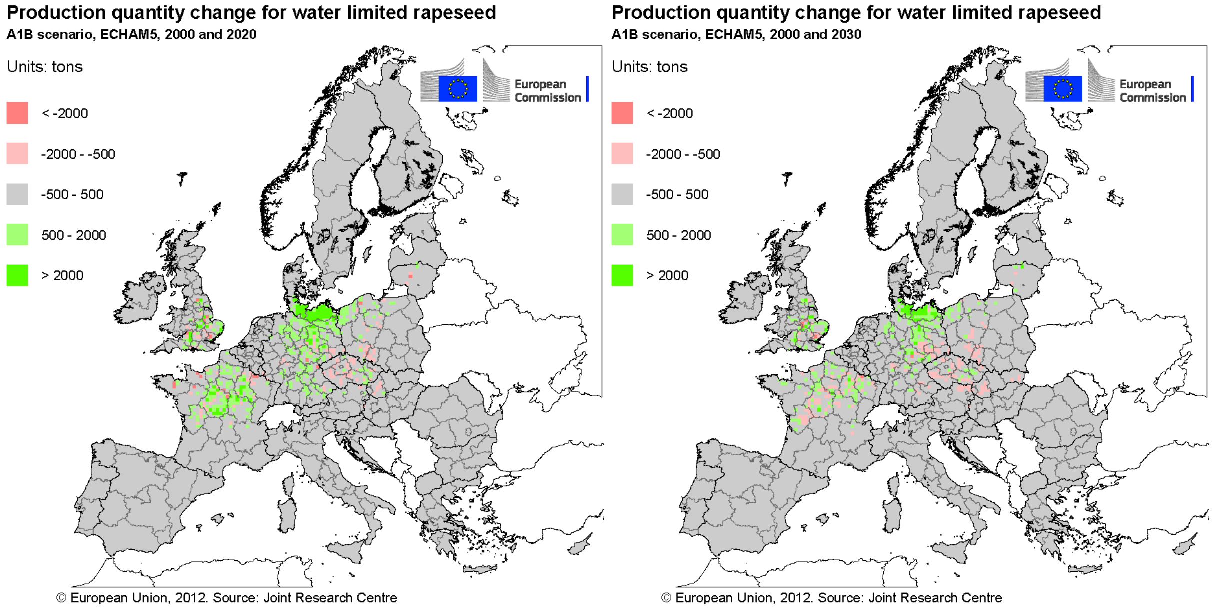


Figure 98. Change in simulated production for water-limited rapeseed between 2000-2020 and 2000-2030, cold scenario. No adaptation considered.

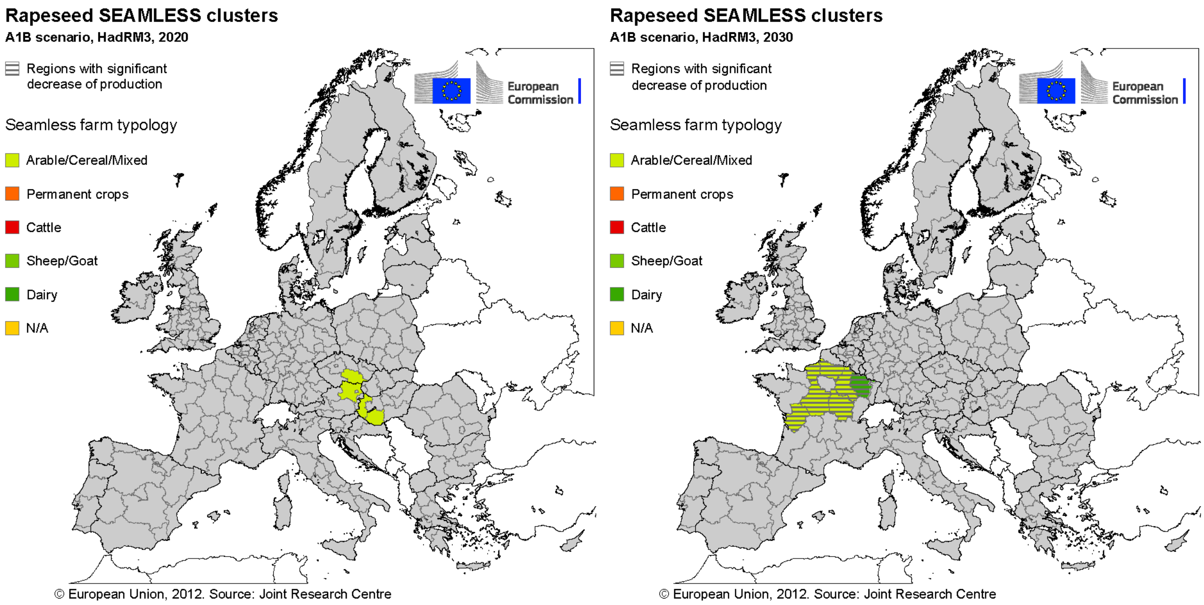


Figure 99. NUTS2 regions showing significant variation in simulated production for rapeseed in 2000-2020 and 2000-2030, warm scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered

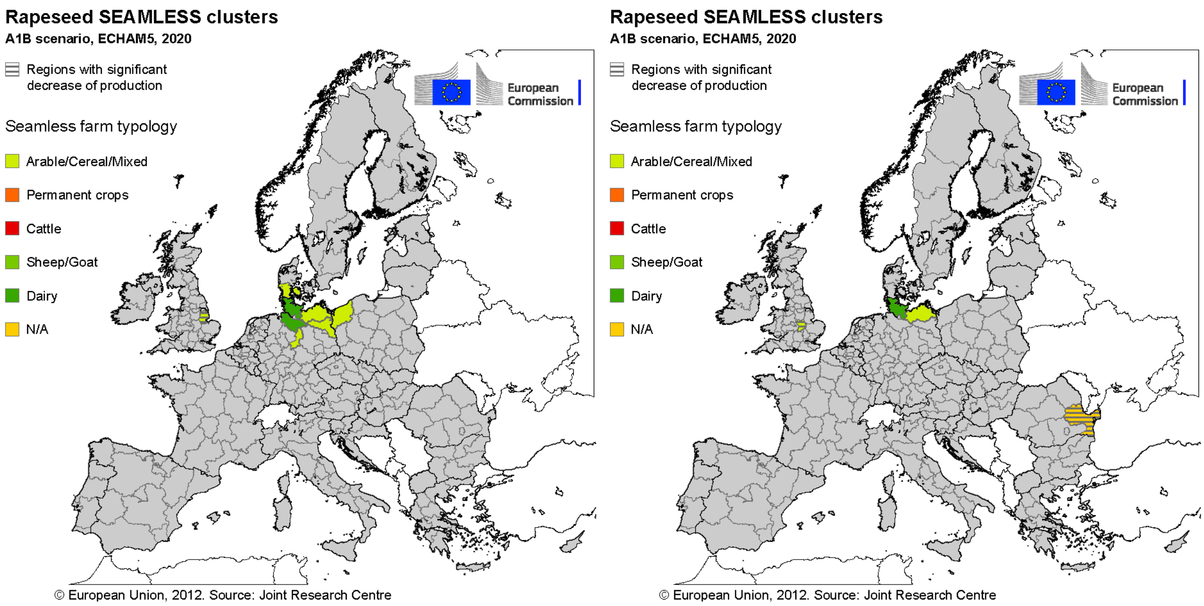


Figure 100. NUTS2 regions showing significant variation in simulated production for rapeseed in 2000-2020 and 2000-2030, cold scenario. The colour indicates the dominant farm typology. Regions in plain colour indicate a significant increase while regions with overlaying stripes indicate there is a significant decrease in production. No adaptation considered

Table 22. Significant production variations in French NUTS2 for rapeseed "warm" scenario, water limited, normalised, tons

nuts2	name	Seamless classification	average ESTAT	prod AVEMAC 2000	Δ20-bline	Δ30-bline	SIGN 2020 - BASELINE	SIGN 2030 - BASELINE
FR10	Ile de France	A	161.747	178.975	-3%	-19%		
FR21	**Champagne-Ardenne**	**A**	**448.147**	**457.612**	**3%**	**-14%**	**0**	**-1**
FR22	**Picardie**	**A**	**200.613**	**196.878**	**-5%**	**-18%**	**0**	**-1**
FR23	**Haute-Normandie**	**A**	**167.147**	**158.558**	**0%**	**-17%**	**0**	**-1**
FR24	**Centre**	**A**	**733.853**	**800.498**	**1%**	**-16%**	**0**	**-1**
FR25	Basse-Normandie	D	74.133	64.587	3%	-14%		
FR26	**Bourgogne**	**A**	**439.387**	**454.690**	**5%**	**-12%**	**0**	**-1**
FR30	Nord - Pas-de-Calais	A	38.073	15.291	-8%	-18%		
FR41	**Lorraine**	**D**	**396.253**	**372.445**	**4%**	**-11%**	**0**	**-1**
FR42	Alsace	A	13.207	12.603	6%	-4%	0	0
FR43	Franche-Comte	D	66.787	77.041	6%	-7%		
FR51	Pays de la Loire	D	102.240	72.577	0%	-16%		
FR52	Bretagne	D	68.807	29.762	-7%	-12%		
FR53	**Poitou-Charentes**	**A**	**286.520**	**273.789**	**-10%**	**-18%**	**0**	**-1**
FR61	Aquitaine	A	17.393	9.876	-8%	-19%		
FR62	Midi-Pyrenees	A	69.160	28.231	5%	-12%		
FR63	Limousin	C	5.893	13.768	-8%	-8%		
FR71	Rhone-Alpes	D	45.553	26.703	12%	3%		
FR72	Auvergne	C	42.473	47.284	15%	-5%		
FR81	Languedoc-Roussillon	B	9.460	1.444	18%	-7%		
FR82	Provence-Alpes-Cote dAzur	B	7.947	-	-	-		
FR			**3.394.793**	**3.292.612**	**1%**	**-14%**		

5.3. Farming systems in NUTS2 Region affected by changes (CAPRI data)

France

Wheat

The analysis was carried out in NUT2 regions where the expected decrease in wheat production in 2030 (warm scenario) is considered as very significant according to the statistical model (P>0,99). Taking into account CAPRI farming specialisation and farm size, the table shows farming types where wheat area represents more than 25% in the NUTS2 region concerned or where wheat area accounts for more than 40% of UAA in the farming type concerned (it must be noted that it is not the repartition within a single farm).

Specialist cereal crops and general field cropping/mixed cropping are the farming types affected by a significant decrease of productions. They refer to farms of medium and big size. Only in Lorraine mixed crop-livestock big size farms seem to be affected by a significant reduction in wheat production.

Table 23. Results of analysis for wheat in France (for farm specialization and farm type codes refer to tables 2 and 3 and for NUTS2 codes to table 16 in this chapter)

NUTS2 code	Farm specialization	Farm size	Code 2	Utilized agricultural area UAAR (ha '000)	Soft wheat SWHE (ha '000)	% wheat region	% wheat / UAA	% area wheat in region>25	% in UAA>40
FR21	1	8	FR210 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... FR210018	377,59	95,34	26,23	25,25	1	0
FR21	2	8	FR210 - FT14_60 / GT100 - General field cropping (FT 14) + Mixed croppi... FR210028	395,91	91,3	25,12	23,06	1	0
FR22	1	7	FR220 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... FR220017	148,97	63,35	12,03	42,53	0	1
FR22	1	8	FR220 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... FR220018	278,94	117,75	22,37	42,21	0	1
FR22	2	7	FR220 - FT14_60 / GT16L100 - General field cropping (FT 14) + Mixed croppi... FR220027	97,69	41,41	7,87	42,39	0	1
FR22	2	8	FR220 - FT14_60 / GT100 - General field cropping (FT 14) + Mixed croppi... FR220028	525,18	212,22	40,31	40,41	1	1
FR24	1	7	FR240 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... FR240017	893,54	262,66	40,82	29,4	1	0
FR24	1	8	FR240 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... FR240018	801,92	235,98	36,67	29,43	1	0
FR30	1	7	FR300 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... FR300017	51,36	20,74	8,42	40,38	0	1

NUTS2 code	Farm specialization	Farm size	Code 2	Utilized agricultural area UAAR (ha '000)	Soft wheat SWHE (ha '000)	% wheat region	% wheat / UAA	% area wheat in region>25	% in UAA>40
FR30	2	8	FR300 - FT14_60 / GT100 - General field cropping (FT 14) + Mixed croppi... FR300028	188,31	70,03	28,44	37,19	1	0
FR41	1	8	FR410 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... FR410018	196,52	50,72	26,11	25,81	1	0
FR41	8	8	FR410 - FT8 / GT100 - Mixed crops-livestock (FT 8) FR410088	275,36	49,2	25,33	17,87	1	0
FR52	3	7	FR520 - FT41 / GT16L100 - Specialist dairying (FT 41) FR520037	730,73	81	27,13	11,08	1	0

Poland

Wheat

The analysis was carried out in NUT2 regions where the expected decrease in wheat production in 2030 (warm scenario) is considered as very significant according to the statistical model (P>0,99). Taking into account CAPRI farming specialisation and farm size, the table shows farming types where wheat area represents more than 20% in the NUTS2 region concerned or where wheat area accounts for more than 30% of UAA in the farming type concerned.
The foreseen reduction of wheat production should generally impact small size farms specialised in general field cropping/mixed cropping and mixed crops-livestock. Only in a few regions the decrease in production will affect specialist cereal farm types (e.g. in Zachodniopomorskie it will concern specialist cereal big size farms).

Table 24. Results of the analysis for wheat in Poland (for farm specialization and farm type codes refer to tables 2 and 3 and for NUTS2 codes to table 18 in this chapter)

NUTS 2 code	Farm specialization	Farm size	Code 2	Utilized agricultural area UAAR (ha '000)	Soft wheat SWHE (ha '000)	% wheat region	% wheat / UAA	% area wheat in region>20	% in UAA>30
PL11	2	6	PL110 - FT14_60 / L16 - General field cropping (FT 14) + Mixed croppi... PL110026	165,38	17,1	23,6	10,34	1	0
PL11	8	6	PL110 - FT8 / L16 - Mixed crops-livestock (FT 8) PL110086	259,17	16,69	23,04	6,44	1	0
PL12	8	6	PL120 - FT8 / L16 - Mixed crops-livestock (FT 8) PL120086	438,71	24,21	20,52	5,52	1	0
PL12	99	9	PL120 - RESTYP / RESESU - Aggregated Rest PL120999	442,66	23,79	20,16	5,37	1	0
PL22	99	9	PL220 - RESTYP / RESESU - Aggregated Rest PL220999	163,88	14,58	32,47	8,9	1	0
PL31	2	6	PL310 - FT14_60 / L16 - General field cropping (FT 14) + Mixed croppi... PL310026	400,53	83,08	32,42	20,74	1	0
PL31	8	6	PL310 - FT8 / L16 - Mixed crops-livestock (FT 8) PL310086	375,64	61,17	23,87	16,28	1	0
PL32	2	6	PL320 - FT14_60 / L16 - General field cropping (FT 14) + Mixed croppi... PL320026	162,34	29,46	27,38	18,15	1	0
PL32	8	6	PL320 - FT8 / L16 - Mixed crops-livestock (FT 8) PL320086	211,89	31,95	29,69	15,08	1	0
PL33	2	6	PL330 - FT14_60 / L16 - General field cropping (FT 14) + Mixed croppi... PL330026	189,43	26,64	34	14,06	1	0
PL33	8	6	PL330 - FT8 / L16 - Mixed crops-livestock (FT 8) PL330086	185,47	22,6	28,84	12,19	1	0

NUTS 2 code	Farm specialization	Farm size	Code 2	Utilized agricultural area UAAR (ha '000)	Soft wheat SWHE (ha '000)	% wheat region	% wheat / UAA	% area wheat in region>20	% in UAA>30
PL34	99	9	PL340 - RESTYP / RESESU - Aggregated Rest PL340999	140,77	15,15	30,03	10,76	1	0
PL41	99	9	PL410 - RESTYP / RESESU - Aggregated Rest PL410999	487,07	45,42	32,54	9,33	1	0
PL42	1	8	PL420 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... PL420018	217,44	61,15	29,18	28,12	1	0
PL51	1	6	PL510 - FT13 / L16 - Specialist cereals, oilseed and protein crops... PL510016	170,19	49,07	22,48	28,83	1	0
PL52	2	6	PL520 - FT14_60 / L16 - General field cropping (FT 14) + Mixed croppi... PL520026	43,32	13,3	10,49	30,7	0	1
PL52	99	9	PL520 - RESTYP / RESESU - Aggregated Rest PL520999	130,38	26,67	21,03	20,46	1	0
PL61	99	9	PL610 - RESTYP / RESESU - Aggregated Rest PL610999	316,2	57,65	34,66	18,23	1	0
PL62	1	7	PL620 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... PL620017	79,83	26,02	16,37	32,59	0	1
PL62	99	9	PL620 - RESTYP / RESESU - Aggregated Rest PL620999	544,67	89,93	56,58	16,51	1	0
PL63	1	6	PL630 - FT13 / L16 - Specialist cereals, oilseed and protein crops... PL630016	52,98	16,91	11,69	31,92	0	1
PL63	8	8	PL630 - FT8 / GT100 - Mixed crops-livestock (FT 8) PL630088	57,81	18,7	12,92	32,35	0	1

Hungary

Sunflower

The analysis was carried out in NUT2 regions where the expected decrease in sunflower production in 2030 (warm scenario) is considered as very significant according to the statistical model (P>0,99). Taking into account CAPRI farming specialisation and farm size, the table shows farming types where sunflower area represents more than 25% in the NUTS2 region concerned or where sunflower area accounts for more than 10% of UAA in the farming type concerned.

The expected decrease of sunflower production will impact specialist cereal, oilseed and protein crops farms of medium and big size.

Table 25. Results of the analysis for sunflower in Hungary (for farm specialization and farm type codes refer to tables 2 and 3 and for NUTS2 codes to table 12 in this chapter)

NUTS 2 code	Farm special ization	Far m size	Code 2	Utilized agricul-tural area UAAR (ha '000)	Sun flower (ha'000)	% sun flower / region	% sun flower / UAA	% area sun flower in region> 25%	% in UAA>1 0
HU10	01	7	HU100 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... HU100017	64,95	6,86	29,29	10,56	1	1
HU10	01	8	HU100 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... HU100018	50,78	6,62	28,27	13,04	1	1
HU22	01	7	HU220 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... HU220017	122,9	4,81	26,74	3,91	1	0
HU23	01	8	HU230 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... HU230018	237,41	6,26	34,68	2,64	1	0
HU31	01	7	HU310 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... HU310017	122,6	13,67	28,00	11,15	1	1
HU31	01	8	HU310 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... HU310018	102,17	11,43	23,41	11,19	0	1
HU32	01	6	HU320 - FT13 / L16 - Specialist cereals, oilseed and protein crops... HU320016	235,08	20,95	25,19	8,91	1	0
HU32	01	7	HU320 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... HU320017	145,96	17,84	21,45	12,22	0	1
HU32	01	8	HU320 - FT13 / GT100 - Specialist cereals, oilseed and protein crops... HU320018	111,22	11,52	13,85	10,36	0	1

NUTS 2 code	Farm special ization	Far m size	Code 2	Utilized agricul-tural area UAAR (ha '000)	Sun flower (ha'000)	% sun flower / region	% sun flower / UAA	% area sun flower in region> 25%	% in UAA>1 0
HU33	01	7	HU330 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops… HU330017	160,1	12,81	25,67	8,00	1	0

Italy

Grain maize

The analysis was carried out in NUT2 regions where the expected decrease in grain maize production in 2030 (warm scenario) is considered as very significant according to the statistical model (P>0,99). Taking into account CAPRI farming specialisation and farm size, the table shows farming types where grain maize area represents more than 25% in the NUTS2 region concerned or where grain maize area accounts for more than 50% of UAA in the farming type concerned.
The expected decline in grain maize will affect mixed crops-livestock and specialist granivores farms and, at a small extent, specialist cereal crops farms. The farms involved are generally medium and big size farms. As mixed crops-livestock farms are also affected, the impact of variation may be higher as these farms could have fewer opportunities to adapt compared to specialist cereal crops farms.

Table 26. Results of the analysis for maize in Italy (for farm specialization and farm type codes refer to tables 2 and 3 and for NUTS2 codes to table 17 in this chapter)

NUTS 2 code	Farm specia lizatio n	Far m size	Code 2	Utilized agricultur al area UAAR (ha '000)	Grain maize (ha'00 0)	% grain maize / region	% grain maize / UAA	% area grain maize in region>25	% in UAA>50
ITC1	01	7	IT110 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... IT110017	142,07	56,6	32,87	39,84	1	0
ITC1	06	7	IT110 – FT50 / GT16L100 - Specialist granivores (FT 50) IT110067	4,09	2,14	1,24	52,32	0	1
ITC1	06	8	IT110 - FT50 / GT100 - Specialist granivores (FT 50) IT110068	5,29	2,74	1,59	51,80	0	1
ITC4	01	7	IT200 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... IT200017	182,49	118,09	34,89	64,71	1	1
ITC4	06	8	IT200 - FT50 / GT100 - Specialist granivores (FT 50) IT200068	23,29	17,25	5,10	74,07	0	1
ITC4	08	7	IT200 - FT8 / GT16L100 - Mixed crops-livestock (FT 8) IT200087	27,25	13,99	4,13	51,34	0	1
ITC4	08	8	IT200 - FT8 / GT100 - Mixed crops-livestock (FT 8) IT200088	39,12	23,54	6,95	60,17	0	1
ITD3	01	6	IT320 - FT13 / L16 - Specialist cereals, oilseed and protein crops... IT320016	212,72	146,69	29,13	68,96	1	1
ITD3	01	7	IT320 - FT13 / GT16L100 - Specialist cereals, oilseed and protein crops... IT320017	135,18	81,03	16,09	59,94	0	1
ITD3	08	8	IT320 - FT8 / GT100 - Mixed crops-livestock (FT 8) IT320088	17,14	9,5	1,89	55,43	0	1

NUTS 2 code	Farm specialization	Farm size	Code 2	Utilized agricultural area UAAR (ha '000)	Grain maize (ha'000)	% grain maize / region	% grain maize / UAA	% area grain maize in region>25	% in UAA>50
ITD3	99	9	IT320 - RESTYP / RESESU - Aggregated Rest IT320999	913,11	204,79	40,67	22,43	1	0
ITD5	99	9	IT400 - RESTYP / RESESU - Aggregated Rest IT400999	388,15	80,28	39,10	20,68	1	0
ITE2	99	9	IT520 - RESTYP / RESESU - Aggregated Rest IT520999	169,12	7,04	25,07	4,16	1	0

6. Methodological framework for policy support

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6.1. Pathways of analysis

Introduction

The main goal of the analysis of agricultural systems under scenarios of climate change is to estimate the impact on production system that cannot be alleviated via adaptation, and the estimate of use of the corresponding resources required. Also, adaptation should be evaluated via indicators of its potential environmental impact (possibly considering its potential mitigation value). The limits identified in the endogenous adaptation achievable set the vulnerability of production systems in specific contexts, and can be the target of specific policies. Within the biophysical evaluation of production systems, the ones of interest in the real world are many as resulting from the combinations of diverse agricultural management, soils, and weather patterns. This, in principle, leads either to specializing analysis in limited contexts (e.g. a typology of farm in a given environment, a region), or to abstract from context specific systems. Technical adaptation can be the result of the combination of single actions, any of which may cause an impact at a much larger scale, thus requiring, according to the goal of the analysis, a fine level of detail in a bottom-up building of adaptation strategies. When the analysis is integrated considering socio-economic analysis, the picture becomes even more articulated. Prior to presenting a possible workplan to address the analysis of agriculture and climate change with a continental coverage, in this work package focusing on the biophysical domain, the possible typologies of analysis are summarized.

Typologies of analysis

The level of abstraction in representing agricultural production and the scales at which such abstraction can be applied are shown in Figure 101. The figure shows also possible pathways of integration between bio-physical and bio-economic models. Bio-economic analysis is considered by definition closer to the real systems, as it includes elements of the bio-physical analysis in an economic driven modelling. The possible links between the different levels of abstractions lead to analysis with a partially different target, different data requirements, and different assumptions. The spatial scale also refers to a level of abstraction, and it should probably be referred to as coverage. In other terms, the response of a crop for a unit area, typically a grid cell, not only abstracts the production system, but it also abstracts its actual presence in the cell. Moving from such abstractions to the actual area represented is a modelling layer to aggregate results such as the one of farm typologies, which may or may not be applied to the analysis. Further, abstracting to production (from average yield) requires estimating, again via a modelling layer, considering technological gaps and variability in the represented area. In no case an abstraction given by a simulation level can be simply used to directly compute estimates of production, then aggregated and compared to statistics.

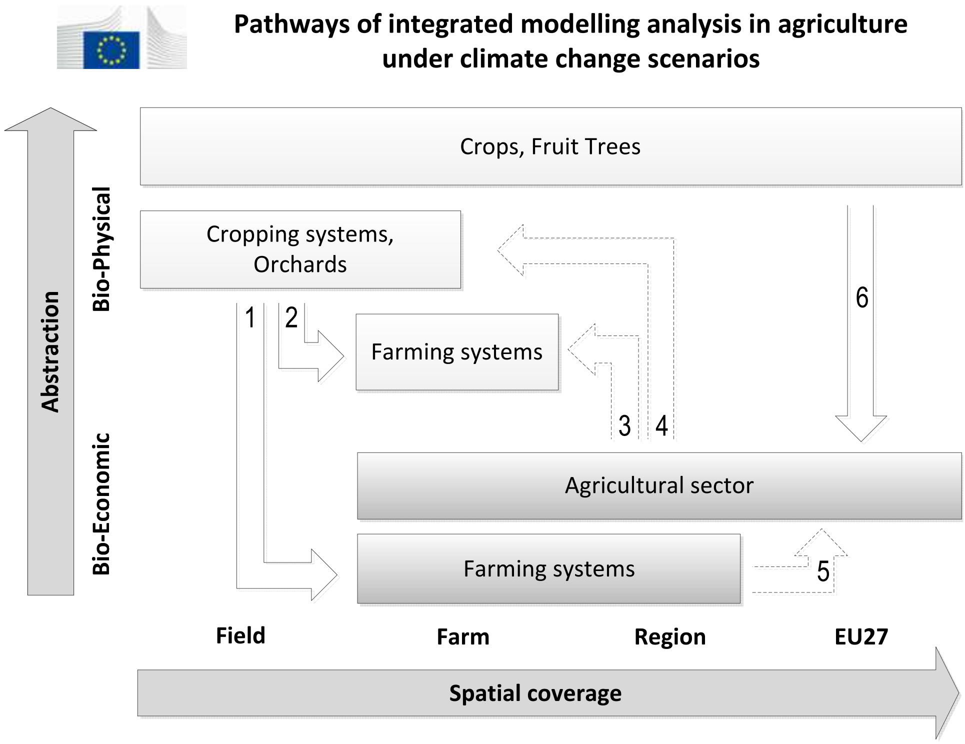


Figure 101 Possible pathways of modelling integration for analysis of agriculture and climate change. Solid arrows represent links already tested, whereas dotted arrows represent pathway still under development (see text for details).

The following paragraphs summarize the main features of the possible analysis as diagrammatically represented in Figure 101. These features will be at the basis of the possible work plans that will be presented. The links of Figure 101 will be commented after the description of the features of the different typologies of analysis. Moving from one typology to the following in the sequence presented, extra layers of data (or outputs) are in bold italics and add to what is requested/made available by the previous analysis.

Bio-physical

Crop

Description: The analysis abstracts a crop from the context given by specific soils and a cropping system (crop sequence, nutrients, tillage etc.), but it can account for irrigation.
Type of analysis: Estimation of the impact of temperature (continuous and as extremes), CO_2, and water availability on specific crops. Further details:

- Data: Weather, crop parameters;
- Time frame: >= ~50 years;
- Spatial dimension: Field;

- Type of output: Biomass production, potential yield, phenology, (potential yield affected by plant disease and by insects);
- Mitigation & adaptation: Explore responses due to known genetic variability, genotype ideotyping;
- Environmental analysis: No;
- Technical resources analysis: No;
- Tools: Crop simulation models;
- Constraints: Detailed spatial information to derive crop parameters and current planting times per unit area with uniform coverage of Europe; lack of capability of simulating the pathogen complex for a crop.

Fruit trees

Description: The analysis abstracts a tree from the context given by specific soils and agricultural management (nutrients, tillage etc.), but it can account for irrigation.
Type of analysis: Estimation of the impact of temperature (continuous and as extremes), CO_2, and water availability on specific tree species. Further details:

- Data: Weather, tree parameters;
- Time frame: >= ~50 years;
- Spatial dimension: Field;
- Type of output: Potential yield, phenology, potential yield, (potential yield affected by plant disease and by insects);
- Mitigation & adaptation: Explore responses due to known genetic variability;
- Environmental analysis: No;
- Technical resources analysis: No (possible abstraction on water use);
- Tools: Tree simulation models;
- Constraints: Detailed spatial information to derive tree parameters per unit area with uniform coverage of Europe; lack of capability of simulating the pathogen complex for a crop; ***tree models (yield, quality).***

Cropping System

Description: The analysis evaluates system performance in specific contexts given by specific soils and agricultural management.
Type of analysis: Estimation of the impact of temperature, CO_2, rainfall, production means on production systems, estimation of system externalities. More details:

- Data: weather, crop parameters, ***soil, agro-management;***
- Time frame: ***short term to ~25 years;***
- Spatial dimension: Field;
- Type of output: ***Potential/water/nitrogen/diseases/insects limited yield, water/nitrogen/pesticides use;***
- Mitigation & adaptation: ***Resource use, rotations (crop sequences), adaptation of growth cycle (genotype & planting), GHG emissions, potential land allocation;***
- Environmental analysis: ***System externalities, soil fertility;***

- Technical resources analysis: Water, ***nitrogen, pesticides, (labour can be derived);***
- Tools: Cropping system simulation models;
- Constraints: Lack of capability of simulating the pathogen complex for a crop, ***weak simulation of vegetables-based systems.***

Orchards

Description: The analysis evaluates system performance in specific contexts given by specific soils and agricultural management.
Type of analysis: Estimation of the impact of temperature, CO_2, rainfall on fruit tree based production systems, estimation of system externalities. Further details:

- Data: weather, tree parameters, ***soil, agro-management;***
- Time frame: ***short term to ~20 years;***
- Spatial dimension: Field;
- Type of output: ***Potential/water/nitrogen/diseases/insects limited yield, water/nitrogen/pesticides use;***
- Mitigation & adaptation: ***Resource use, GHG emissions, potential land allocation;***
- Environmental analysis: ***System externalities, soil fertility;***
- Technical resources analysis: Water, ***nitrogen, pesticides, (labour can be derived);***
- Tools: Orchards/vineyards/olives simulation models;
- Constraints: Lack of capability of simulating the pathogen complex for a tree, Orchards/vineyards/olives models (yield and quality), ***lack of information on orchards based systems.***

Farming systems

Description: The analysis evaluates farm performance as composed by different production enterprises, which compete for technical resources and labour.
Type of analysis: Estimation of the impact of temperature, CO_2, rainfall on ***production enterprises in a farm***. Further details:

- Data: weather, parameters of the species, soil, agro-management, ***farm data;***
- Time frame: short term to ~20 years;
- Spatial dimension: farm;
- Mitigation & adaptation: water and nitrogen use, GHG emissions, ***adaptation of growth cycle in crop sequences (genotype), production enterprise;***
- Environmental analysis: Resource use, system externalities, soil fertility;
- Technical resources analysis: Water, nitrogen, labour, ***competition for agro-management implementation;***
- Tools: ***Farm simulation models;***
- Constraints: ***Amount of farm data, representativeness of farms;***

A note on pasture, grassland, and livestock systems

There is substantial difference in considering grassland and pasture in simulation analyses. Grassland can be simulated using generic crop simulators. Pasture, instead, cannot be abstracted covering large areas, as for grasses, because of the poor representativeness of the abstraction that would be given by the same type of approach used for crops at 25 x 25 km^2 grid. Whether grassland (e.g. alfalfa or Italian ryegrass) can be represented as growing on a common, synthetic soil profile, pasture by definition is grown on marginal soils which vary greatly by slope, soil depth and exposure. Even assuming a simulation as biomass production with no grazing (which would imply e very detailed, context specific, layer of information), a context specific simulation is required. The simulation of livestock systems as open systems is also possible, and very relevant if mitigation potential is evaluated; in any case, the level of abstraction of the production system and its interface with farms must be clarified in context specific analysis, unless basic, generic responses of animals to temperature are of interest. Both for pasture and livestock systems, the analysis should be considered in the second phase of a possible analysis as discussed below.

Final remarks

A noticeable upgrade in the typology of analysis is represented by introducing aspects related to emissions, and more in general to environmental impact. Addressing indicators of environmental interest requires the simulation of both carbon and nitrogen in the soil. Modelling of soil nitrogen is extremely critical because of its general level of empiricism in most cropping system models, definitely higher than both the one of soil water and plant growth modelling. The level of empiricism is due to ignoring explicitly the dynamics of the soil microbial communities of fungi and bacteria, which govern the transformations from soil organic matter to mineral nitrogen, and which are responsible for transformations from one form of mineral nitrogen to another. The dynamics of nitrogen in the soil are modelled as responses to temperature and water which impact on microbial communities, via the proxies represented by various pools of organic matter. The reason why the level of empiricism of nitrogen modelling does not impede using these models in various environments is due to robustness of parameters according to soil typologies. However, model parameters have no biological meaning and cannot be used in modelling approaches different from the ones for which they have been calibrated for. The consequence is the need of a more detailed set of information from environments compared to what is requested for instance for soil water and crops.

Bio-economic

Farming systems

Type of analysis: optimize management in a farm (profit, risk). Further details:

- Data: all data required to obtain biophysical estimates, socio-economic (labour, finances, cash flow), regulations (policy and environmental measures), farm data (technical constraints);
- Time frame: short term to ~20 years;
- Spatial dimension: Farm;
- Type of output: optimization of management scenarios, economic parameters;
- Mitigation & adaptation: Optimization of biophysical systems (including technical adaptation) in economic terms;
- Environmental analysis: Subjected to estimating a value for environmental costs/services;
- Tools: Farm bio-economic models (micro economic models);
- Constraints: Amount of farm data, representativeness of farms, price scenarios (also linked to regulations).

Agricultural sector

Description: Agricultural sector model to evaluate *ex-ante* impacts of the Common Agricultural Policy and trade policies on production, income, markets, trade, and the environment, from global to regional scale.
Type of analysis: Assessing the impact of CAP at EU-27 but also at sub-national level (including farm types change). More details:

- Data: all data required to obtain biophysical estimates, data from EUROSTAT, FAOSTAT, OECD and extractions from the Farm Accounting Data Network (FADN);
- Time frame: short term to ~20 years;
- Spatial dimension: EU;
- Type of output: impacts of the Common Agricultural Policy and trade policies on production, income, markets, trade;
- Mitigation & adaptation: analysis of biophysical systems (including technical adaptation) in economic terms;
- Environmental analysis: ***Coarse, static, post processing;***
- Tools: ***Supply/market models, models to sample farm types, interpolation and aggregation of supply behaviour results obtained from farm models;***
- Constraints: Amount of farm data, representativeness of farms, ***link of several tools, data heterogeneity Member States.***

6.2. Biophysical Modelling

Given the description of biophysical modelling approaches and of simulation procedures done in chapter 3, this section focuses on concepts related to the possible extension of the AVEMAC study.

Adaptation

Crop assessment studies must take into account adaptation potential and quantify the degree to which negative impacts can be minimized through management, in order to be credible. Adaptation strategies can be subdivided into two groups: autonomous/short-term adaptations and planned/long-term adaptations (Tubiello et al., 2009; Bates et al., 2008; Olesen and Bindi, 2002). Responses implemented by farmers, rural communities or farmer's organizations, taking into account real or perceived climate change, to optimize production without major system changes, pertain to the former group; while structural changes guided by interventions at the regional, national or international levels, that involves other sectors (e.g. policy, research, etc.), are planned/long-term adaptations (Carpani et al., 2011; Biesbroek at al., 2010).

The adaptation strategies considered in most studies are basic technical options, likely available to farmers today. This implies that alleviation to the impact of climate change was estimated on the basis of the same abstraction of production system evaluated in the baseline simulations (i.e., referred to current conditions). There has not been consideration of agent-based feedback to the building of adaptation strategies—neither from agricultural sector models nor from farm models—capable of identifying further option for production systems (e.g., new crops), and setting constraints due to technology, funding and resource limitations, or both. This is a limit because it does not allow further specialization in evaluating systems of potential interest, first via bio-physical simulation, then via bio-economic evaluation. Also, very often no innovation (e.g. new genotypes) has been tested. This hypothesis can be considered mostly adequate for short to mid term (i.e. 2020-2030), but need to be appropriately extended if a broader time horizon is considered.

There is, however, a limit in considering adaptation beyond, say, 15-20 years from current time, for three reasons. Firstly, the adaptation we can study applies to systems which will not have major, unpredictable changes in the near future as it is likely to occur as resulting from technical innovation. It would have little sense in defining detailed management pathways on systems which may change substantially. Secondly, as discussed in the uncertainty section, the uncertainty in the weather scenarios, within a specific emission scenario, grow and become a major source of variation in the simulation outputs, hence making alleviation measures possibly impacting only on a fraction of the total variability. Thirdly, the bio-economic analysis is based on variants on known systems, hence neither being able to make quantitative estimates of economic performance for new systems, nor to provide feedbacks to optimize systems.

Uncertainty

Input data

Uncertainty related to input data is related to data quality in broad terms (i.e. part of the input data are also model outputs) and to the variability due to stochastic components (primarily, weather). The two are often confounded. Uncertainty can be tested within realization scenario via impact models, testing the significance of difference of means (e.g. the mean of the baseline and of 2030, both based on multiple years). In this case, assuming that data quality is the same for both time horizons, the significance of the difference may be the basis to develop adaptation strategies, otherwise statistically unjustified.
However, a realization of an emission scenario is part of the picture. Should two realizations of the same emission scenario result partially different, typically for rainfall, they will lead, as observed with the two examples used, to a very variable population. In this case, the test of difference between means would include all the outputs of the impact model (i.e. obtained using both series of input weather data) for a given time horizon, to be contrasted against all the outputs of the impact model for the baseline. As an example, the south-east part of Spain can be considered. One realization estimates reductions in rainfall, whereas the other estimates an increase; if the outputs of the impact model are pooled together, there will not be any difference with respect to baseline conditions likely not even as a mean. The test pooling outputs from different scenarios is hence much more critical than the one within one realization of an emission scenario. If both realizations of the emission scenario are considered equally reliable, this test quantifies statistical tests of mean differences between time horizons.
It must be pointed out that running tests as above treats all observation points as equally probable, whereas only one GCM model, at a given time, will result closer to the real system. This suggests keeping tests within realizations of emission scenarios, allowing the choice either to consider the most severe impact assessment (to be conservative with respect to risk), or to consider both to explore policies to support adaptation.

Weather scenarios

There is broad variability of GCM estimates within emission scenario. As discussed above in general terms, the statistical approach would lead to almost no significant difference, especially in short to medium-term time horizons. Estimates must be kept separated for the analysis of the worst-case possible scenario.

Agro-management data

The production systems simulated are abstractions of the many possible systems in the real world. The representativeness of agro-management practices, especially when doing context-specific analyses, but also for biophysical model calibration, is a limiting factor in building abstraction of systems to be analysed. Ultimately, for alternate agro-management practices, a database specifically targeted to provide inputs for simulations must be developed.

Reference data

The only reference data covering the whole EU27 territory are aggregated statistics as discussed in the section of calibration. Such data only in limited cases can be used as reference data to be compared/associated to point simulations. A database of reference data to be articulated according to production level needs to be built to increase the reliability and the representativeness of model estimates.

Processing and output data

The workflow from raw weather data to impact assessment via simulation models is articulated as discussed in the methodology of this project and even further as articulated for a richer analysis as presented here. The multiplicity of cases given by the EU27 coverage in the two phases envisioned demands for the development of procedures for a systematic check of all procedures in the workflow, improving not only the reliability of the processing, but also increasing its transparency improving the capability to take advantage of expert knowledge when available. The development of an articulated analysis of agricultural production and climate change would hence require the further development of the BioMA platform with tools and utilities dedicated to quality assurance.

Model uncertainty

Model calibration was discussed under the crop models limitations and assumptions section of WP2. The uncertainty of agro-management inputs in the first instance as discussed above, and the limited reference data to be used for calibration, introduce uncertainty on the representativeness of the abstraction used using a simulation at 25 x 25 km^2. According to the uneven data availability across EU27, the level of representativeness of simulations will be variable across EU27, requiring a concrete action to improve the reference data set. It must be pointed out, however, that this aspect is particularly critical for the second phase of the analysis as described below.

The capability of a crop simulation model in representing the real system must be seen in the terms of the shift from simulating condition of good adaptation for crops to conditions in which the range of air temperature and other environmental parameters may lead to crop failure, thus requiring simulating crop response in a more articulated way. The simulation models in BioMA, as discussed before in the crop evaluation section of WP2, implement such responses, and more will be done to further improve model simulations. In a situation like this, using model ensembles would not be beneficial because models failing the hypothesis of good adaptation of crop can be considered *a priori* risky for simulations under climate change. It must be pointed out that such considerations should have been made also when using models developed for temperate areas in different environments, characterized by temperature extremes, but discussing this aspect is beyond the scope of this work package. In summary, state of that art models must be used having clear that model evaluation for scenarios of climate change is very limited.

Conclusive remarks

Statistical tests should be performed to quantify uncertainty and significance of mean differences whenever possible. However, neither a rigorous test can be made at each step of the workflow, including the evaluation of the inputs used, nor there is complete knowledge of errors and uncertainty. Consequently, from an operational point of view, two main actions must be implemented at all levels of abstraction considered:

- Whenever a source of uncertainty is identified (e.g. emission scenarios realizations, crop parameters), parallel analysis should be run;
- Whenever an updated version of either a key data layer or a modelling engine is available, the analysis should be rerun.

The corresponding either alternate or updated results must be presented to stakeholders.

6.3.Agri-economic modelling

In this section a proposal for an economic modelling framework is presented, for which two remarks have to be highlighted:

- The quantitative methods that need be developed should not only be based on econometric models, but also on farm-level optimization models.
- In order to incorporate the externalised environmental costs into the economic analysis validated data should be provided from other quantitative assessment studies.

Therefore, with these two main considerations in mind, the following will introduce the socio-economic assessment of climate change, followed by a description of the main components of modelling the impacts, ending with the "state of the art" and potential developments of quantitative assessment of policies and adaptation.

The socio-economic assessment of climate change adaptation measures require building a comprehensive economic modelling framework which considers economic and environmental inter-linkages and feedbacks present in the agricultural sector as well as the complexity of the farming systems and adaptive agro-technological processes. As discussed in the previous sections, the climate change effects are transmitted onto the agricultural sector by altering biophysical processes of agro-ecosystems for example by shifting productivity potential and by altering agronomic-environmental conditions. This requires and integrated modelling approach between bio-physical and economic modelling through an iterative process. An additional important consideration is the global dimension of the climate change. The interrelation of world regions through trade induces indirect impacts transmitted through price signals on agricultural markets and adaptation processes. The global market feedbacks are crucial component of the economic modelling approach and allow accounting for the indirect trade induced consequences of climate change which may have offsetting or strengthening effects on EU agriculture.

The main objective of the economic modelling framework under climate change scenario is to analyse the impact on the EU agricultural sector, farming systems and environment to provide prospective analysis of measures improving resilience and limiting future exposure to damages and shortages in support for policy making.

Main components of modelling economic impacts of climate change

Three key dimensions can be distinguished when modelling the economic impacts of climate change:

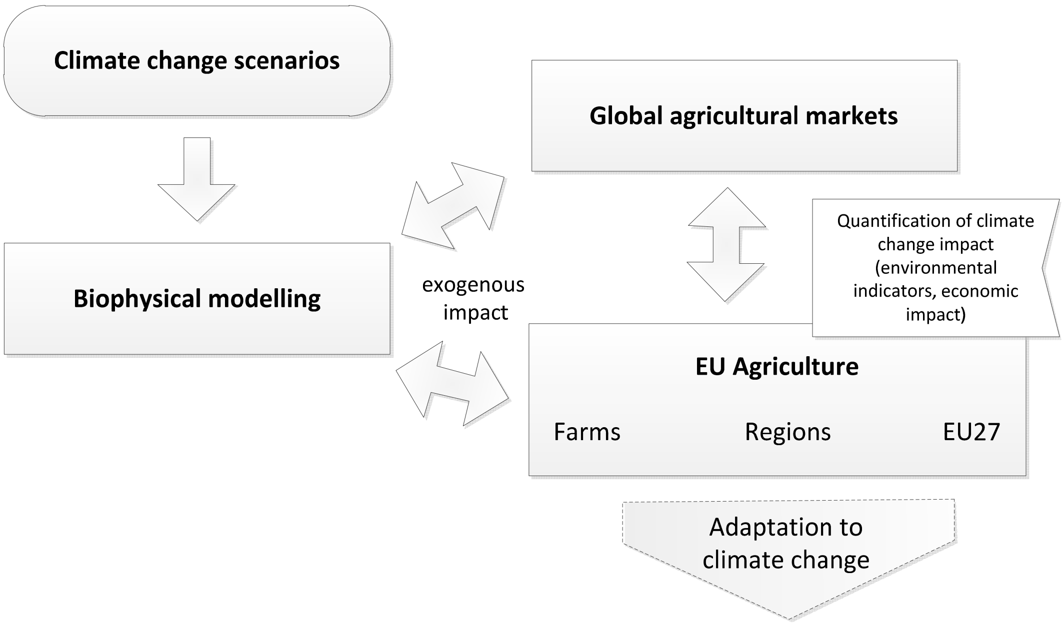
- Type of response analysed: short/medium term adjustment versus long-term adaptation of the agricultural sector and farming systems;
- Disaggregation level of the agricultural sector: micro (e.g. farm) versus macro (e.g. regional, EU) level;
- Model inter-linkages: interaction between bio-physical processes, farms, EU regions and global markets.

Figure 114 shows a generic representation of the components of modelling economic impacts of climate change. It considers scales, as in figure 111, focusing on Economic components. Climate change impacts the bio-physical processes of agro-ecosystems and represents an exogenous changing factor for the sector.

The adjustment/adaptation of the agricultural sector to these changes consists of various effects and depends on the perspective of the analyses and abstraction level.

One possible level of analysis represents a short/medium term adjustment versus a long-term adaptation of the agricultural sector and farming systems to climate change (Olesen and Bindi, 2002; Schneider et al., 2000). The short/medium term adjustment includes adjustment of production without major system changes related for example to farm practises and farm structures. The long-term adaptation refers to major structural changes to farming systems. The degree of agricultural sector response to climate change closely relates to and depends on the expectation of the agents regarding climate change, knowledge and foresight of their impacts, adaptive capacity, speed of technological development and policy responses.

A second level of analyses considers different disaggregation levels of the agricultural sector. A micro approach (e.g. farm level) allows a more detailed analysis of responses, adjustments and adaptations to climate change such as technological innovations, sustainability of farm practices, land allocation patterns, income distributional effects, etc. At a higher level of abstraction (e.g. regional, EU) the main focus of analyses are more aggregated impacts such as market effects on prices, supply and trade, food self-sufficiency, regional differences, land use, environment, global feedbacks, etc.
Multi-scale interconnections among models and model disaggregation are needed in order to capture both the exogenous and endogenous reactions of bio-physical processes as well as economic feedbacks and inter-linkages among agents and markets. Exogenous impacts coming from an adjustment of bio-physical processes to climate change induce first order endogenous responses at micro level (e.g. farms) which are transmitted to regional and global levels through supply responses. The impacts represent the various types of reactions of the agricultural sector depending on the type of response considered and on the disaggregation level of analyses. Furthermore, a second order endogenous feedback from the market, to the regions, farms and bio-physical processes, is induced through the changed pressures and demands of agricultural production on agro-ecosystems. These feedbacks will continue iteratively until the equilibrium is reached.



	Farms	Regions	EU-27 and global effects
Short/Medium term adjustment	- Farm production structure adjustment (substitution between crops)	- Regional production structure adjustment	- Supply and trade structure adjustment and relative price changes
	- management practices fertilizers and pesticides use water use tillage practices extensification	- Input use changes and availability (e.g water) and indirect regional productivity change	- Input price adjustment and indirect supply/price effects
	- Management practices on factors of production (land, capital, labour)	- Regional adjustment on parameters of land, labour, capital effects	Regional adjustment on parameters of land, labour, capital effects
Long term adaptation	- Adaptation of technology	- Regional variation technological adaptation and productivity change	- EU competitiveness, supply response and trade adjustment and output price effects
	- Farms structural effects (e.g. exit, farm size, re-specialization)	- Regional production structure adjustment, labour use - Farm typologies	- Output market impacts, labour market impacts - EU farm typologies
	- Structural adjustment of land use	- Regional land use changes and land market effects	- EU and global land use changes and land market effects

Figure 102. Climate change impacts and linkages

The economic modelling challenges: state of the art and potential development

This section describes the challenges faced when modelling the economic impacts of climate change and highlights the potential developments that may be considered necessary for conducting an effective policy impact analysis.
Models need to take into account multi-scale interconnections among different model components in order to capture climate change impacts on the agricultural sector. Three response effects of the agricultural sector to climate change can be distinguished: exogenous shock, first-order endogenous adjustment/ adaptation, second-order endogenous adjustment/ adaptation (Table 27).

The exogenous shock refers to a shift in production potential induced by changes in the bio-physical process due to climate change. This step necessitates the consideration of a specific link between bio-physical models and economic models whereby a climate change scenario is introduced into a bio-physical model which is further linked to an economic model by altering productivity parameters in the economic model (e.g. yields).

The endogenous adjustment/ adaptation considers the reaction of the agricultural sector to this exogenous shock induced by climate change. In terms of modelling this is captured through representation of the structural and behavioural relationships present within the agricultural sector. The endogenous reaction of the agricultural sector can be distinguished as being first-order or second order adjustments/ adaptations.

- The first-order endogenous reaction represents a direct adjustment/ adaptation of the agricultural sector to the altered production potential induced by climate change. It includes, for example, change in supply, production structure, input use, technology, farm structure, etc. depending on the type of response analysed and the disaggregation level. In principle, the first-order effects represent the changes in agricultural sector production fundamentals and in modelling terms it is mainly captured through the supply module.
- The second order endogenous response is an indirect effect of climate change. It represents the market response to changed fundamentals in production potential and it encompasses feedback reactions transmitted from the market module to the supply module and the bio-physical model (e.g. adjustment of yields, farm practices due to market price effects). The market response is transmitted mainly through price signals as a result of the supply interaction on the EU and global markets.

The medium term adjustments can be relatively well captured with the current available models (e.g. CAPRI). This is particularly the case at EU/global, regional and/or farm-type level where both the exogenous shock and the endogenous adjustments to climate change are explicitly modelled. This includes a detailed representation of farm-type and regional supply modules, as well as EU and global market interactions. However, it will be necessary to extend the farm level modelling (e.g. CAPRI-FARM, FSSIM) to better take into account the adjustment of farm management practices to climate change. At the same time, a more explicit feedback between economic and bio-physical models needs to be integrated into the simulation process to incorporate the endogenous responses of agro-ecosystems to agricultural sector adjustments.
Modelling the long-term adaptation of the agricultural sector to climate change is more challenging. The key component in this respect is farm level modelling. The long-term adaptation implies modelling, among other things, farm structural changes, farm technological choices and adaptation of farm practices. The current available models do not adequately capture these effects, particularly if one considers EU-wide level analysis. The models would need to be extended to a more explicit representation of farms and would need to endogenise farm behavioural parameters. The actual extension/development of farm level modelling depends on the perspective of analyses and abstraction level.

When modelling climate change impacts several key constraints and challenges need to be taken into account:

- *Data availability*. One important constraint in modelling climate change effects is data availability. To model the adaptation of the agricultural sector detailed data are required on production technology and farm economics, ideally at farm level, thus allowing the parameterisation of farm level models (e.g. FSSIM). Different data sources may be required to be combined: results from different models (e.g. data derived from the bio-physical model) data from official sources (e.g. FADN, FSS) and complementary secondary sources (e.g. farm survey, literature).
- *Time horizon*. From a climate change perspective, modelling a more distant time horizon is more realistic as the effects are long-run impacts. However, from an agricultural modelling sector perspective, considering lung-run impacts may lead to misrepresentation of structural changes in agriculture. There is a need to strike a balance between reducing the error of misrepresenting structural changes on the one hand and climate change consideration on the other.

- *Expectation of the agents and technological development.* The degree of agricultural sector response to climate change closely relates to and depends on the expectation of the agents regarding climate changes, their adaptive capacity and the speed of technological development. Exact representation of these factors is subject to data availability although they are often uncertain and therefore difficult to model in a long-run horizon. These considerations strongly determine the parameterisation of the model and the sensitivity of the results.
- *Integration among the different models.* To achieve an operational model chain for applications in order to assess climate change (or any other impact affecting the farming systems) a semantic, conceptual and technical integration is needed. As the modelling framework will combine different quantitative models (e.g. bio-physical, bio-economic, market) from different disciplines and therefore with different spatial and temporal resolution of data, it is important to achieve a consistent linkage of the simulated processes and scales. In addition, this modelling integration should take into consideration the potential feedback between models.
- *Uncertainty in analyzing climate change*. Modelling climate change is subject to many uncertainties. The exact impact of climate change depends on the development of several uncertain elements. In particular it is difficult to predict the exact development of the bio-physical processes, the technological development and the agents' behavioural change. These elements are captured in the modelling exercise through model parameters, behavioural relationships, technological choices, etc., that will strongly determine the actual climate change impacts. As future climate change related events might have a range of expected values also dependent on the resolution of the analysis (e.g. temporal, regional, disaggregation level), this may require the incorporation of an uncertainty analysis into the modelling exercise (e.g. sensitivity analysis).

Table 27. Typology of adjustment/adaptation to climate change

	Description	Examples	
		Short/Medium term adjustment	**Long term adaptation**
Exogenous shock	Climate change impact is linked to bio-physical model leading to yield adjustment at farm/regional/EU level		
Endogenous first-order adjustment/ adaptation	Response of farms and regions and markets to yield change due to climate change	Farm production response, adjustment of input use, change of production structure	Farm production response, adaptation of technology, crop varieties, change in farm structure, change of production structure
Endogenous second-order adjustment/ adaptation	Feedback from markets to regions, farms and bio-physical model	Further adjustment of production and farm practices due to price effects	Further adaptation of production and technology due to price effects

Policy aspects of climate change

The purpose of developing the economic modelling of climate change is to provide a platform for a comprehensive impact assessment of policy scenarios. This is relevant in several respects:

- to develop of a prospective analysis of measures to improve resilience and limit future exposure to damages and shortages,
- to model the role of the CAP in addressing climate objectives,
- to estimate the environmental and economic implications of climate change policies relative to the counterfactual situation,
- to compare alternative policy measures,
- to identify the sensitivity of the simulation results to climate change policies,
- to provide the potential impacts and consequences of shifting towards a low-carbon and climate-resilient economy in the agricultural sector.

In broad terms the aim is to cover both two interlinked types of policies: (i) *climate mitigation policies and (ii) climate adaptation policies.*

- *Climate mitigation policies* refer to measures aiming to eliminate or reduce the sources of climate change impacts on the agricultural sector. Examples of climate mitigation policies include policy induced incentives that limit the harmful impact of economic activities on climate, such as the adoption of improved management practices designed to reduce emissions and increase the sequestering of carbon. The instruments for achieving this reduction could be implemented by market measures (e.g. taxes or emissions trading schemes) or command and control measures.

- *Climate adaptation policies* refer to measures supporting the ability of the agricultural sector to adjust to climate change to moderate potential damage, to take advantage of opportunities, or to cope with the consequences. The International Panel on Climate Change (IPCC) defines adaptation as the, "*adjustment in natural or human systems to a new or changing environment. Adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.*" Potential adaptation polices include support for certain farm technology and management practices, agri-environmental climate payments, development of new farming systems, CAP payments for agricultural practises beneficial to the climate and the environment ("greening" measures), introduction of new crop varieties, land use related policies, etc.

Adaptation measures target behavioural aspects of the agricultural sector and for this reason they require a higher level of modelling complexity than mitigation policies. Their modelling is more demanding in terms of data needs, modelling the intervention logic of policies, estimation of model parameters, assumptions on possible development of technologies, modelling farm practices and farm structural changes.

Mitigation policies focus more on the intensity and efficiency aspects of agricultural production and their link to climate change; hence modelling the mitigation impact of climate change is less complex.

However, the ability to model specific mitigation or adaptation policies depends on the perspective of the analyses and the abstraction level. In particular the key-determining factor is the type of response considered and the disaggregation level of the analyses. For example, comprehensive modelling at micro level and of long term adaptation may permit modellers to better model and evaluate policies than when climate change modelling is implemented at regional or country levels.

6.4. Linking bio-physical to agri-economic models

There is no commonly accepted and defined methodology in linking models developed within different domains. Problems of scale add to error and uncertainty propagation. Also, examples exist in literature in which linear programming was used for composing and optimizing factors in biophysical systems which are highly non-linear.

Current pathways of analysis

Referring to Figure 101, there are two pathways of analysis at different level of abstraction that have been used so far, corresponding mostly to two levels of abstraction. The link between crop and agricultural sector models corresponds to highest level of abstraction, in the figure linked via the connector 6. The link is one-directional and implemented making available to the bio-economic model yield data obtained under reference (baseline) and climate scenarios. Several assumptions are made both on the bio-physical and on the bio-economic side, and are described in WP6. The second type of analysis is more context-specific, and the link between bio-physical and bio-economic models is represented by the connector 1. As described in the types of analysis, this workflow potentially allows targeting also environmental aspects and ecosystem services as part of production systems evaluation. It also produces output that allows considering green house gases emissions and carbon sequestration, hence allowing an evaluation of mitigation potential. This type of work flow can be further extended linking the Bio-economic model on farming systems to the agricultural sector model (connector 5), via an econometric meta-model describing price-production responses of farms given specific farm resources and biophysical characteristics, hence improving the supply module of the agricultural sector model. The connector 4 shows a possible path to impose constraints in the building of technical adaptation options, hence allowing for an economic-driven choice/validation of adaptation options. Finally, the connector 3 would allow an ex-post technical validation of farming systems optimized via the bio-economic models.

A two-phases analysis

A generalized and detailed analysis of the many production systems in the different environments is resource and data limited, if targeting EU27 Member States. Given that an analysis using the same methodology is however required, this leads to select the highest levels of abstraction as in Figure 101 as possible analysis. The results of this analysis can have multiple stakeholders, as described in the relevant section. One major output would be the identification of potential hot spots of vulnerability, which can be purely bio-physical or bio-economic. Estimating which are the areas that potentially may not auto-adapt to the changed environmental conditions shows the areas to prioritize for possible intervention either to facilitate endogenous adaptation or to provide external support to buffer specific adversities. However, the identification of area of potential vulnerability via a high level of abstraction analysis does not account both for the specificity of systems which may not be fully represented by the abstraction chosen, and in any case for potential resiliency of the specific production systems. Moreover, as discussed in presenting the typologies of analysis, the analysis at the highest level of abstraction does not allow accounting, if marginally, for aspects related to environmental impact and mitigation potential.
The analysis should then be integrated with a finer resolution analysis, using cropping system/orchards models as bio-physical models, and with a farm models as bio-economic model to confirm and quantify the estimate of vulnerability, both from the bio-physical and bio-economic perspective. A pathway for such two-phase analysis is represented in Figure 103, showing a possible feedback to the supply module of the agricultural sector model. This second phase analysis may be run in bilateral, direct cooperation, with relevant Member States, providing expert knowledge and integrating with the data needed in all phases of the simulation process.

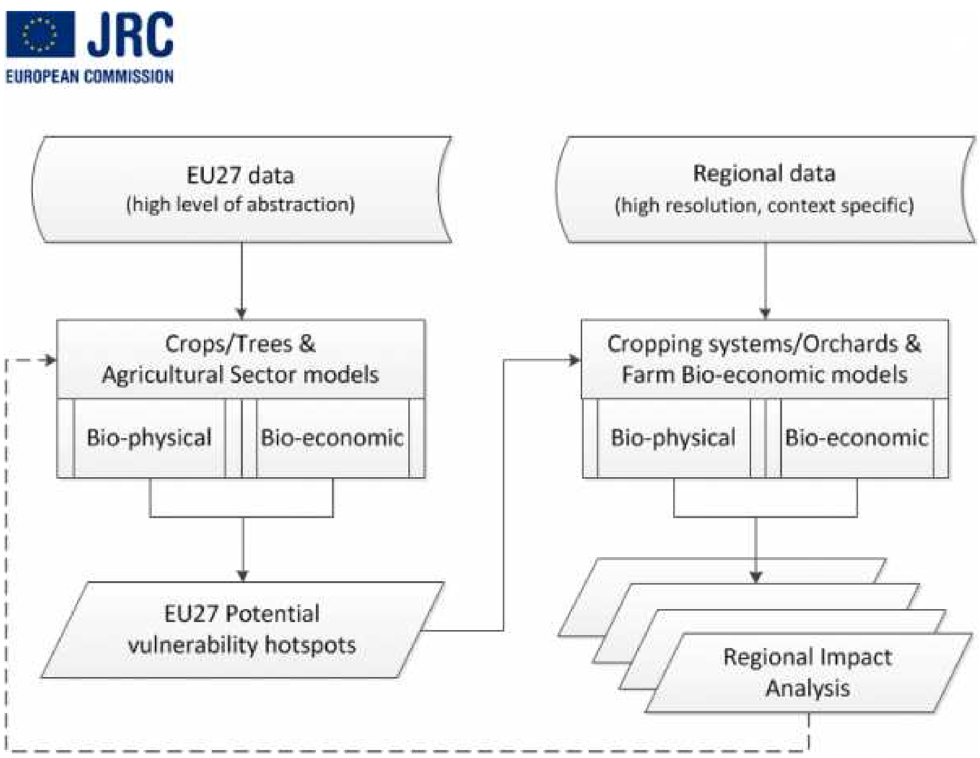


Figure 103 Analysing adaptation of agricultural systems in two phases: from high level of abstraction to context specific analysis in potentially vulnerable areas.

Representativeness of systems

Even if a biophysical analysis at the level of "crop" or "tree" abstracts from the production systems as discussed, integrating the information about the unit area chosen for the abstraction improves the representativeness of such abstraction. Using information about slope, irrigation vs. rain-fed percentage of areas used by a crop, main soil typologies, would produce multiple simulation results per unit area. This would not be useful only to the bio-economic analysis to explore variants of proxies for production systems, but would also create a key input (although not the only one needed) to the development of a modelling layer to build a link between simulation and statistics.

Linking to different domains

Adapted systems may require additional resources with respect to current systems, and even the amount currently used may be not available in future scenarios. The typical example is water for irrigation, but also labour, assets, and fuel may be increasingly costly/unavailable. In fact, resources may be subject by multiple demands from various sectors, hence making some hypothesis of adaptation either unrealistic or increasingly costly to the extent of requiring external financial support. Consequently, the development of adaptation strategies to alleviate the impact of climate change requires implementing constraints which can be very dynamic when driven by prices, or structural, as it would be for instance for irrigation water. The constraints due to prices scenarios can be successfully accounted for via the linking to bio-economic models even at the highest levels of abstraction; in fact, prices are marginally context specific, hence not requiring a detailed, context specific, layer of information. Structural constraints instead are context specific, and could be applied in the regional analysis outlined above. The demand from adapted system can be itself an input to the cross-domain modelling of resource use. Another constraint in developing adaptation strategies in agriculture is related to land use, but given the rigidity in allowing switching from rural to urban land use in most countries in Europe, land use changes can be considered exclusively in term of agricultural production enterprise in the limited time horizon of the analysis. Given the multiplicity of the goals of analysis related to climate change and agriculture, and the fast dynamics (prices, some possible technical innovation) one aspect of primary importance is the development of a framework which enables updating analysis under changes of inputs (e.g. the CO_2 concentration currently estimated for 2030 is the one estimated, in the 90', to 2050), also allowing addressing new research questions.

6.5.Platform

Bio-physical

The platform used in AVEMAC is derived from the BioMA - Biophysical Model Applications framework. Both its current capabilities and its extensibility make it an effective tool for further developing an analysis on climate change and agriculture.

Database

The weather database could be integrated with other realizations of different emission scenarios, but it represents already a consistent and articulated base for future analyses. The database of agro-management, crop varieties, soils, and the ones used in the economic analysis as described in the following chapter will require the integration of existing databases, or at least the access to them. It must be clear that such a database could require a substantial work to “distil” data as no standards are available to be used, as an example, for agro-management.

Models

The following sections summarize model description from one hand to list the modelling capabilities already available in the platform, from the other to highlight development needed to meet the goals of the presented analysis on agriculture and climate change. Modelling approaches have been updated to move forward from the assumption of well adapted varieties, hence accounting for higher than optimal temperatures, and of extreme event in the sense of values of environmental variables which cause a direct damage (or death) of an organism.

Crop development and growth

Crop modelling is well developed into the BioMA modelling framework being developed at IES MARS-AGRI4CAST, making available for use at least alternate modelling solutions. An improvement of the part on abiotic stresses must be done for a more uniform coverage of different crop.

Pastures

The implementation of a generic pasture simulator is at start, and it will implement widely known modelling approaches.

Trees

Currently, no tree model is implemented in the modelling platform. Given the large area occupied by grapevine and olive trees, the goal is to implement models for development, growth, and quality of olives and grapevine. The basic structure is available already for grapevine.

Diseases

A generic simulator of air-borne diseases coupled to crop models is implemented in the BioMA framework, making available a unique modelling resource.

Insects

A simulation module for insects is at first stages of development, including currently only the corn borer. Work is needed to extend its simulation capabilities to major crops/vineyard/olive trees.

Cropping systems

An updated version of APES (Agricultural Production and Externalities Simulator), from the FP6 Project SEAMLESS, is implemented in BioMA.

Soil nitrogen and carbon

One of the APES carbon-nitrogen modules is currently being re-factored and will be update the APES one. However, such module does not include the simulation capabilities of greenhouse gases emissions.

Crop suitability

Assessing crop suitability is key to estimate potential changes to crops geographic distribution, either usable as results, to be validated via simulation. On the one hand, it is well known that crops will respond to specific changes in temperature and precipitation at the locations where they are currently grown; on the other, it is also expected that not all crops and cultivars will remain suitable within their current geographical ranges, with tendencies to migrate towards higher latitudes and a push out of production in areas already at the margin of production. Most crop modelling platforms available today present fixed grid simulations of crops, i.e., they do not allow for dynamical movements of ideal crop ranges, and thus tend to underestimate likely adaptation responses by farmers. These will doubtlessly attempt to switch where possible to cultivars and crops better adapted to changing conditions. By the same token, those model platforms that have excelled in computing suitability have much less crop modelling detail than available under the proposed platform.

Estimating crop suitability either defines a modelling layer above the one of biophysical simulations using the outputs of it, or it could be completely disconnected from simulation and be based on static indicators. The Suitability component included in BioMA implements a variety of approaches for suitability estimation based on single-cell (e.g., threshold based approaches) or multi-cell (i.e., based on multiple regressions) computations. Among the approaches implemented, some are

retrieved from the literature, and based on soil and/or weather inputs, e.g., FAO EcoCrop[3], Less Favourable Areas (Eliasson et al., 2010). Other approaches derive a suitability index from simulated variables, like yields, completion of crop cycle, yield gaps due to biotic and abiotic factors affecting productions.
Our implementation of all the methods allow the user to select the methods themselves (i) in their original configuration, and (ii) with options allowing to exclude categories of variables or parameters from the computation. Another criterion is based on the assumption that crop choices by farmers tend to aggregate in production districts. This approach cannot be used alone and the Suitability model component gives the user the possibility of coupling it to all the other methods implemented.

Agri-economic

Two models from the integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) will be used: the agro-economic sector model CAPRI and the farm model FSSIM. A summary description follows.

CAPRI model

CAPRI (Common Agricultural Policy Regionalized Impact Model) is a comparative static partial equilibrium model for the agricultural sector developed for policy and market impact assessments from global to regional and farm type scale (Britz and Witzke, 2008). It is solved by iteratively linking its supply and market modules. The market module is a global spatial Multi-Commodity Model using 28 trade blocs and 60 countries (Figure 104). Based on the Armington approach (Armington, 1986) products are differentiated by origin, enabling to capture bilateral trade flows. The supply module is composed of separate, regional, non-linear programming models. The regional programming models are based on a model template assuming profit-maximizing behaviour under technological constraints, most importantly in animal feeding and fertilizer use, but also constraints on inputs and outputs such as young animal, land balances and set-aside (Jansson and Heckelei, 2011). The supply module currently covers all individual Member States of the EU-27 and also Norway, Turkey and the Western Balkans broken down to about 280 administrative regions (NUTS2 level) and more than 50 agricultural products.
The NUTS2 regions[4] are disaggregated into 1,823 farm-type regional models. The farm type layer (i.e. CAPRI-FARM module) captures heterogeneity in farming practises and farm types within a region, and thus reduces aggregation bias of the CAPRI model. Each single farm type in CAPRI is characterized along two dimensions given by production specialization and the “economic size class” represented in terms of “European size units” (ESU) (Table 28). The farm type layer is built based on data from the Farm Accountancy Data Network (FADN) and the Farm Structure Survey (FSS) data. The farm type layer consists of independent non-linear programming models for each farm type aggregated over all activities belonging to the farm in a specific NUTS2 region. The farm models, similar to the regional ones, capture production structure and policies in high detail including NPK balances and a module with feeding activities covering nutrient requirements of animals. Prices are endogenously determined by the market module in an iterative process solved between the supply and market modules until convergence is reached (Britz and Witzke, 2008). Grass, silage and manure are assumed to be non-tradable and receive shadow prices based on their substitution value and opportunity costs (Gocht and Britz, 2011).

[3] http://ecocrop.fao.org

[4] With the exemption of Bulgaria and Romania

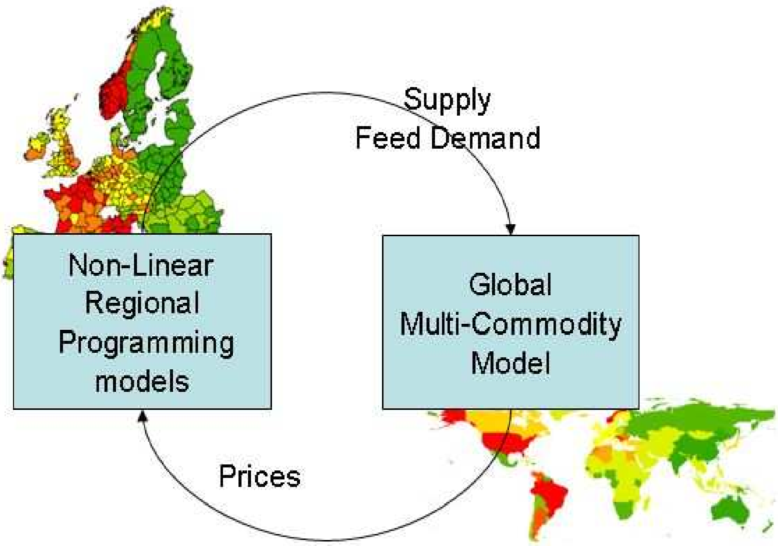


Figure 104: CAPRI model

Table 28: Types of farming and economic size classes for the farm types in CAPRI-FARM

Type of farming		Economic size class	
Specialist cereals, oilseed and protein crops	13	ESC 1	< 16 ESU
General field cropping + Mixed cropping	14_60	ESC 2	≥ 16 ≤ 100 ESU
Specialist horticulture	20	ESC 3	> 100 ESU
Specialist vineyards	31		
Specialist fruit and citrus fruit	32		
Specialist olives	33		
Various permanent crops combined	34		
Specialist dairying	41		
Specialist cattle + dairying rearing, fattening	42_43		
Sheep, goats and other grazing livestock	44		
Specialist granivores	50		
Mixed livestock holdings	70		
Mixed crops-livestock	80		

FSSIM model

(Louhichi, Janssen, et al., 2010; Jansson and Heckelei, 2011; Louhichi, Kanellopoulos, et al., 2010)

FSSIM is a bio-economic farm model developed within the SEAMLESS project, to assess the impact of agricultural and environmental policies on the performance of farms and on indicators of sustainability. It consists of a data module for agricultural management (FSSIM-AM) and a mathematical programming model (FSSIM-MP). FSSIM-AM aims to identify current and alternative activities and to quantify their input and output coefficients (both yields and environmental effects) using the biophysical field model APES (Agricultural Production and Externalities Simulator) and other data sources. Once these activities have been generated, FSSIM-MP chooses those that best fit the farmer's behaviour, given the set of resources, the technological and political constraints, and forecasts farmer responses to new technologies, as well as to policy and market changes (Louhichi, Kanellopoulos, et al., 2010). The principal outputs generated from FSSIM for a specific policy are forecasts on land use, production, input use, farm income and environmental externalities (e.g. nitrogen surplus, nitrate leaching, pesticide use, etc.). These outputs can be used directly or translated into indicators to provide measures of the impact of policies (Figure 105).

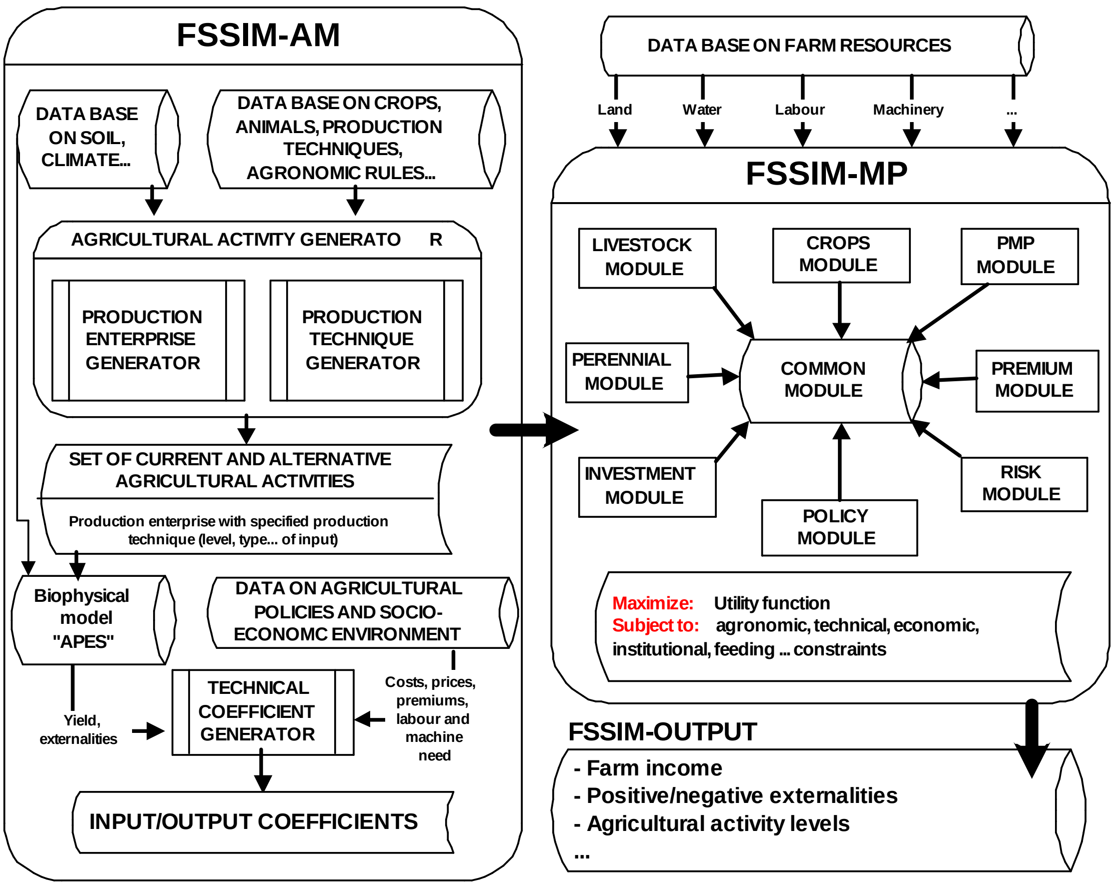


Figure 105. An overview of FSSIM as a combination of Agricultural Management module and Mathematical Programming module (Louhichi et al., 2010b).

FSSIM was designed sufficiently generic and with a transparent syntaxes in order to be applied to many different farming systems across Europe and elsewhere. It has a modular setup to be re-usable, adaptable and easily extendable to achieve different modelling goals. It includes a set of modules, namely crops, perennial, premium, Positive Mathematical Programming (PMP), risk, trend and policy (all separate modules). These modules are solved simultaneously; they are linked indirectly by an integrative module named the "common module" involving the objective function and the common constraints. Thanks to its modularity, FSSIM-MP provides the ability to add and remove modules (and their corresponding constraints) following the needs of the simulation, to select one or several calibration approaches between different options (risk, standard PMP, Rhöm and Dabbert' s PMP approach, Kanellopoulos et al. PMP approach) and to control the flow of data between the database and software tools. FSSIM-MP can be run with simple or detailed survey data (i.e. according to the level of detail of the available data). Additionally, it can read input data stored in any database (e.g. MS ACCESS DB), or include files from Excel or GAMS, provided that they are structured in the required format.

FSSIM can be applied to individual (i.e. real) or representative farm (i.e. typical or average farm) as well as to natural (territorial) or administrative region by considering the selected region as a large farm (i.e. if the heterogeneity among farms inside the region is insignificant) or by aggregating the results of individual or representative farms (i.e. if the inter-dependencies between farms are minors). It can be used for two purposes: (i) to allow detailed regional impact assessment of policy decisions, market change and technological innovations on farming practices and sustainability of the different farming systems; (ii) to facilitate the link of micro and macro levels in integrated way through the estimation of supply-response functions that can be integrated in a partial equilibrium market model.

The mathematical programming module of FSSIM (FSSIM-MP) is a constraint optimization model which maximizes an objective function at given prices and subsidies subject to a set of resource and policy constraints. It consists of a non-linear programming model, which maximizes the farm's utility defined as the expected income minus risk, according to the Mean-Standard deviation method (Hazell and Norton, 1986). FSSIM-MP is referred to as a positive mathematical programming (Howitt, 1995) model which integrates a large number of crop and animal activities.

The main specifications of FSSIM-MP are (Louhichi *et al.*, 1010a):

(i) **A static programming model** which optimizes an objective functions for one period (i.e. one year) over which decisions are taken. This implies that it does not explicitly take account of time. Nevertheless, to incorporate some temporal effects, agricultural activities are based on "crop rotations [5]" and "dressed animal[6]" rather than individual crops and animals.

(ii) **A positive model** in the sense that its empirical applications exploit the observed behaviour of economic agents to reproduce the observed production situation as precisely as possible;

(iii) **An activity based model** what means that one product can be produced by different activities, and each activity can produce several products. This makes suitable the integrated assessment of new policies which are linked to activity and not to product. This is the case or soil conservation policies in the USA, where all farm subsidies depend on the use of specific agricultural practices. In Europe, the Nitrate Directive is also an example of a policy targeting production processes, not products. This approach makes possible to take into account positive and negative jointness in outputs (i.e., joint production)

(iv) **A primal based model** where technology is explicitly represented in order to simulate the switch between production techniques as well as between production systems;

(v) **A discrete based model** to integrate easily the engineering production functions generated from biophysical models and to account positive and negative jointness in outputs (i.e., joint production) associated with the production process. These specifications enable FSSIM to explore the impacts of policy changes and technological innovation not only on the relationship between market and nonmarket goods, but also on the production process.

(vi) **A template based model:** FSSIM-MP uses a model template for all the applications, i.e. the equations and variables used in FSSIM are the same everywhere but the set of parameters depend on farm data

FSSIM has been applied for different climate zones and soil types and to a range of different farm types with different specializations, intensities and sizes. In most applications FSSIM has been used to assess the effects of policy changes (Louhichi et al., 2009; Kanellopoulos et al., 2009; Majewski

[5] Crop rotation is the practice of growing a series of dissimilar types of crops in the same area in sequential seasons for various benefits such as to avoid the build-up of pathogens and pests that often occurs when one species is continuously cropped.

[6] The concept of 'dressed animal' represents an adult animal and young stock taking into account the replacement rate.

et al., 2009; Mouratiadou et al., 2010) and in two applications to assess the impact of technological innovations(Louhichi et al., 2008; Traoré et al., 2009). In the various applications, different data sources, level of detail and model configurations have been used. FSSIM has been linked to an economic and several biophysical models. The model is available for applications to other conditions and research issues, and it is open to be further tested and to be extended with new components, indicators or linkages to other models (Janssen et al., 2010)

Table 29. Comparison between CAPRI-FARM and FSSIM

	Approach	Integrated in modeling chain	Link to biophysical model	spatial resolution	Develop-ment stage	Link to market model	Specific module related to the farm-management practices
CAPRI-FARM	Top-Down (template model based on the NUTS2 regional model)	CAPRI	Partially (DNDC[7])	HSMU[8]	Tested at the EU-25 (not included Romania and Bulgaria)	Yes to CAPRI	NO
FSSIM	Bottom-Up(template model based at the farm-type)	SEAMLESS-IF	Yes (APES[9])	HSMU	At present tested in 12 NUTS2 regions	Yes to SEAMCAP[10]	Yes (FSSIM-AM)[11]

[7] DeNitrification-Decomposition model

[8] Homogenous Soil Mapping Units

[9] Agricultural Production and Externalities Simulator

[10] Adapted version of the Common Agricultural Policy Regional Impact (CAPRI) model

[11] Farm Systems SIMulator-Agricultural Management

6.6.Work plan

Objectives

The following points summarize what discussed in the previous paragraphs as objectives and actions required.

General objectives

Estimate potential vulnerability: bio-physical, agri-economic

The highest level of abstraction in analysing system (the analysis presented in this project completed by adaptation strategies development) may lead to potential estimates of vulnerability, because of its level of abstraction. For the same reason, adaptation is analysed rather than to quantify possible changes in production system, to make an estimate of vulnerability. However, this analysis is a prerequisite to identify areas where a closer to real systems analysis should be made, not being possible to run such an analysis with full coverage of EU27, and to be able to respond quickly to unexpected changes in prices or technology.

Estimate context specific vulnerability and adaptation strategies

The analysis on specific context as indicated as potentially vulnerable would allow building adaptation strategies with the limitations given not only by macro-factors such as prices, but also on resources constraints, and by environmental factors, which require more detail information on the systems to be estimated.

Make operational an integrated modelling framework

The capability of estimating the impact on production systems of new and unpredictable market conditions, new greenhouse gases emission scenarios, and new environmental conditions resulting from monitoring, is key for climate change analyses on agriculture. This can be addressed by setting a "live" framework, which can be updated with new data layers and new modelling tools. The prototype of such framework exist already, and must enriched from one side to a more articulated access to layers of information, and from the other by integrating models which exist but do not have an operational implementation which allows from one side mode composition, from the other the capability of ingest large amounts of data spatially defined.

Specific objectives

- Extend the number of climate scenarios
  - Add weather data of other emission scenarios
  - Add weather data of other realizations of A1B

- Improve biophysical model calibration and representativeness of area abstractions
  - Add data layers of current practices and reference data

- Extend biophysical modelling capabilities of the platform
  - Add olive trees (development, growth, and quality models)
  - Add vineyard (development, growth, and quality models)
  - Extend parameterization to other crops

- Develop strategies of biophysical adaptation
  - Per crop, for potential vulnerability assessment
  - Context specific on cropping/farm systems

- Identification of responses

  - Identify relevant behavioural responses from a socio-economic modelling perspective

- Improvement of the current economic models/ development of new modules/models
  - Incorporate/implement climate change relevant variables and interlinkages in the model(s)
  - Improve/implement the modelling of behavioural aspects of climate change
  - Improve/implement model calibration and representativeness of area abstractions
  - Improve/implement baseline construction

- Inter-linkages among different models
  - Improve model inter-linkages between micro-macro level and global market module
  - Develop model inter-linkages between economic model and bio-physical model
  - Implement feed-back from bio-economic analysis to set constraints in adaptation strategies

- Development of perspective of the analyses and the abstraction level
  - Determine disaggregation level of analyses
  - Determine type of response analysed

- Enable context specific analysis adding an environmental dimension in building adaptation scenarios
  - Build context specific database for cropping system (bio-physical) analysis
  - Build context specific database for farms (bio-economic) analysis

- Policy impact analysis.
  - Improve modelling of policy intervention logic
  - Identify relevant climate change scenarios
  - Develop policy scenarios
  - Identify causal relationships

- Modelling constraints: horizontal developments
  - Identify constraints in terms of data, model assumptions and sensitivity of modelling results

Target stakeholders

Target stakeholder can be identified as:

- European Commission

For the analysis on the potential vulnerability and for the context specific analysis, which may contribute to specific policies for adaptation development.

- Member States

For the potential vulnerability analysis (if excluding areas considered as vulnerable by national analyses), and for the context specific analysis which would be of direct relevance for a country.

- Growers associations/extension services

For specific technical aspects such as diseases potential spreading, use of water, changes in production systems.

Methodology

The methodology would complete and extend what done in the AVEMAC project, having necessarily a focus on bio-physical and bio-economic models.

Work flow

The phases of the analysis are the ones presented in Figure 103; each of the phases can be summarized by Figure 106, having the feedback link from bio-economic modelling to bio-physical modelling a meaning partially different, due to the different level of abstraction of the two phases. At highest level of abstraction the link would set constraints given by macro-factors, such as prices and polices, whereas in context specific analysis resources availability (e.g. water, labour, farm typology) would also impact.

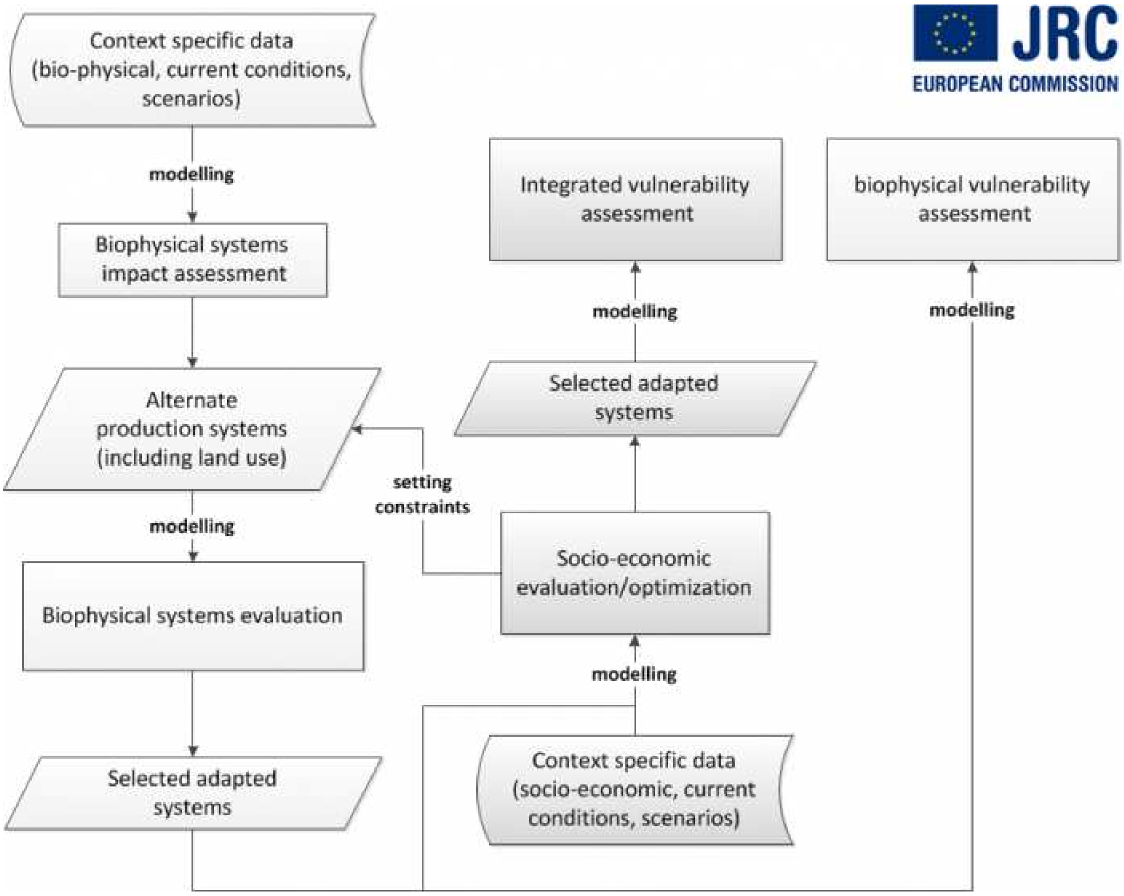


Figure 106 Macro-workflow for bio-physical and bio-economic analysis to assess vulnerability of agricultural production under scenarios of climate change. This workflow is the same for the two-phases analysis presented in Figure 103, with the difference of producing in phase one an estimate of potential vulnerability, and of using different models (crop-tree/agricultural sector vs. cropping system-orchard/farm models).

Actions and time frame

The analysis summarized in the paragraphs above is articulated within action and it implies two macro-phases at least in a sequence. A **minimum time frame must be considered of two years**, whereas completing the analysis with the implementation of modelling capabilities currently not operational within the modelling frameworks available would require a third year. However, the various phases and steps summarized for the analysis would allow producing intermediate results, allowing also an interaction with stakeholders.
In fact, there is neither a "conclusive" nor a "comprehensive" analysis possible, hence requiring an extensible platform that needs to build a state of the art analysis tool for problems of agriculture and climate change. In this perspective, rather than envisioning a 2-3 years project, a medium term activity, based on periods of two years, may build an operational activity addressing various issues to be addressed at EU27 level and related to agriculture and climate change. Such issues would also include a possible re-running of the analysis once updated knowledge (data, models) becomes

available. This activity may include active interaction with Member States particularly on the phase two outlined above, also facilitating the development of harmonized (in terms of both knowledge and methodology) plans for action by Member States.

Resources

The amount of resources can be defined in detail when developing a specific project. However, some general aspects can be stated:

- At least three Actions of the Joint Research Centre would need to be involved to cover the aspects of crop simulations including adaptation, of evaluating agri-environmental impacts, and of the transfer simulated yields to production and the impact at farm level;
- Experience of this study shows that considerable IT capacity and support are required for the pre-processing of large input datasets and the execution of a high number of model runs resulting from combinations of different time horizons, crops, production abstractions, adaptation measures, etc.;
- Each Action would require a dedicated scientist and supporting scientific staff at post-doc level;
- Cooperation with external research institutions would be limited to addressing specific modelling issues, hence with resources use not higher than 10-15% of the total.

Conclusions and recommendations

Two key aspects must be considered when evaluating the results of this study:

- Firstly, this analysis does not include in the simulations any technical adaptation of the abstraction of production systems. However, in reality some level of adaptation will occur autonomously by farmers; hence a potential impact assessment should consider impacts net of the alleviation given by such adaptation.
- The second important aspect is the level of abstraction for production levels.

This exploratory analysis has simulated one production system per crop and unit area. The abstraction may represent the crop productivity with a different level of reliability when the production context is very diversified, e.g. by different cropping systems or soils, within the unit area considered. Consequently, the results should not be analysed focusing on specific unit areas. This is of even greater importance when moving from unit area yield estimates to production estimates.

The two weather scenarios considered as realizations of global circulation models of the IPCC A1B emission scenario do not differ remarkably on air temperature, but they show differences in precipitation patterns comparing Southern and Central Northern Europe. Results are presented in terms of differences from baseline results. Different types of policy support strategies can be envisaged based on the simulation results obtained and on their differences with respect to the two studied realizations. The differences of simulation results of the two scenarios as presented could lead to different choices in the approaches using the results as input for policy support. For example, results of both realizations could be pooled against the baseline in order to represent the entire spectrum of possible outcomes, which might be required for a certain type of policies. Other types of policy strategies might be more adequately based on either the most extreme, or the most conservative, realization of the IPCC scenario, or one of them could be chosen, either being the most extreme one or the most conservative one, to support different policy options.

The increase of temperature has produced articulated pictures according to the crop considered, due to the specific combination of thermal requirements and period of growth of the crop during the year. When evaluating yield with the option of no limitations of production by water, diseases, etc., positive factors were the increased photosynthesis efficiency due to elevated CO_2 concentrations as carbon fertilization and the improved thermal regime. At the same time, however, the latter may have led to a shortening of the grain-filling phase in crops. The evaluation of potential yield may provide suggestions with respect to some features of improved varieties. On the other hand, when evaluating water limited yields, other factors such as avoidance of stress as well as the timing and amount of use of water may lead to different genetic crop ideotypes as compared to potential conditions.

The main results of the study in terms of crop yields are:

- Under potential production wheat showed a negative response at northern latitudes, and mostly unchanged yield response at southern latitudes.
- The picture resulted differently for rapeseed, with a negative potential impact especially at southern latitudes.
- Sunflower took advantage of the improved thermal regime at northern latitudes, but showed negative effects due to the shortening of the grain-filling phase at southern latitudes.

- Maize responded positively at northern latitudes because of the increase of temperatures, but showed a decline of potential yield due to the shortening of the grain-filling phase at southern latitudes.
- Yield development at the potential production level was estimated to be positive for rice, due to the improvement of the thermal regime and the beneficial effect of increased CO_2 concentrations from carbon fertilization. At the same time, rice is not grown at latitudes where the increase of temperature could have detrimental results in a similar manner to maize.
- The analysis of grapevine phenology, again to be considered an analysis under potential conditions, shows articulated differences in the phenology of early, medium maturity, and late varieties. Qualitative aspects of vines are tightly related to the concept of *terroir*, hence related to the matching of grapes to an articulated set of conditions. Consequently, the analysis projects a large potential vulnerability of vine production and quality.

When water-limited yield is considered, the different precipitation patterns estimated by the two GCMs led to a different response of rain-fed crops (wheat, rapeseed, sunflower), which, in the case of HadCM3-derived weather data, project an improvement of yields in Southern Europe. In the case of ECHAM5-derived weather data, a smaller impact on yields resulted from the simulations of the rain-fed crops in Southern Europe. This was due both to the better avoidance of summer water stress and the beneficial effect of increased CO_2 concentrations with respect to the baseline. Compared to other crops, maize showed a distinct behaviour with respect to water supply. When needed, a maximum of three irrigations were simulated in the model simulations, mimicking limited water supply practices of maize when grown using irrigation. Such limited irrigation proved to be sufficient in the 2020 scenario in order to not show differences with respect to baseline, but inadequate in the 2030 scenario that provides higher air temperatures. It must also be pointed out that maize, because of its internal pathway to photosynthesis, does not benefit from the increased CO_2 concentrations and associated carbon fertilization as much as the other crops analysed.

The diseases impact on yield, limited to potential production in the current study, will have to be extended to water limited production, broadened to additional diseases per crop, and revised to better assess the reliability of the model parameterization used. For these reasons the outcome of the disease limited simulations must be considered preliminary. Nevertheless, the results showed a sizeable impact on crops compared to current conditions.

The classification of areas with climate constraints via static weather indicators has shown minor and mostly positive changes, comparing the baseline period centred on the year 2000 to the 2020 and 2030 time horizons. In general, results of the estimates for 2020 and 2030 show the same trend, with more pronounced changes visible for 2030. Areas in Finland, Sweden, and Scotland classified as constrained in 2000 are estimated as not constrained any more in 2030 due to increases in mean annual air temperature. Estimates with the “warm” HadCM3 realization of the A1B emission scenario produced a stronger reduction in constrained areas then the “cold” ECHAM5 realization. While the Mediterranean region experiences almost no changes in constrained regions in the HadCM3-derived estimates for 2030, there is a slight increase of constrained areas for the ECHAM5-based estimates. For south-east Europe the two realizations of the A1B scenario produce results in the opposite direction: While in the HadCM3 realization the constrained areas decrease due to increasing precipitation (Hungary), in the ECHAM5-dervied estimates areas with a climate constraint increase by 2030 as a consequence of a decrease in precipitation (Hungary, Romania, Bulgaria).

The results of the analysis at the basic unit area level were extended to production estimates and to impacts at farm level under the hypothesis of null adaptation as discussed in the opening paragraph.

In terms of quantitative changes in crop production, results are very heterogeneous in space and magnitude:

- For maize, estimates of the warm scenario for 2030 indicated in the whole EU a potential decrease of about 9% in the production of grain maize in comparison to the 2000 baseline. The decrease would affect 36 NUTS2 regions. These regions are mainly located in important countries for grain maize production such as France, Romania, Italy, Hungary and Spain and are mostly characterised by cereal and mixed farming systems. An opposite situation is foreseen by the cold scenario with a potential increase of the EU overall production of grain maize both in 2020 and 2030 compared to the baseline. Many regions in Italy, Spain, Romania and Greece are expected to have an increase of production, in some cases quite important (+15-20%). The cold scenario foresees a stable production in France.

- Regarding sunflower, the analysis of the warm scenario for 2030 indicates a potential decrease in sunflower production of around 10% for all important Spanish production regions. Potential decreases in sunflower production are estimated for France, too, however with a smaller decrease from 4% to 8% depending on the region. All regions in Hungary and almost all regions in Bulgaria and Romania are estimated to be potentially affected by a significant decrease in 2030. At country level resulting figures show a potential decrease of 14% for Romania, 12% for Hungary, and 13% for Bulgaria. The analysis for the cold scenario anticipates to 2020 the variations foreseen in the warm scenario in 2030 for all most important Spanish regions producing sunflower. The 2030 cold scenario almost reflects the results obtained with the warm scenario at least for what concerns the identification of the NUTS2 regions where a significant potential decrease in production can be expected (in Spain, Hungary, Bulgaria and Romania). Different results are obtained for French regions, which seem not to be concerned by a potential diminution of the production in the cold scenario.

- For wheat, according to the warm scenario in 2030, regions in Northern France, Poland, Lithuania and Latvia could be affected by a potential decrease in the order of 8% to 18% that can be considered significant. Regions potentially affected have a dominance of cereal and mixed farming systems. In France some regions that are also potentially affected are characterized by a diverse pattern of farming systems with a relatively high share of dairy farms. On the other hand, analysis results for regions in Italy, Bulgaria, and Spain indicate a significant potential increase in wheat production. These regions are characterised by a dominance of cereal and mixed farming systems. While the “warm scenario” does not foresee any significant decrease of production in 2020, the analysis for the “cold scenario” highlights several NUTS2 regions (mainly in Spain and Poland) that may be potentially affected by a significant decrease of wheat production. On the contrary some Regions in Northern and Western France should register a statistically significant potential increase. The cold scenario for 2030 confirms a significant potential decrease of production in numerous Polish regions. Not expected with the warm scenario, all Romanian, northern Bulgarian and western Hungarian regions will be potentially affected by a significant decrease of production according to the cold scenario.

- For rapeseed, according to the results of the analysis for the warm scenario, only regions in France are estimated to experience a significant potential decrease by 2030 of -11% to -18%, depending on the region. The same regions would have a slightly positive potential increase, even if not significant, when taking into account the cold scenario. These regions are characterized by a prevalence of cereal and mixed farming systems. The analysis for the cold scenario shows some significant potential increase in 2020 only in a few NUTS2 regions located in Northern Germany, Denmark and Poland; most of these variations become insignificant in 2030.

- For rice production no variations are expected for both warm and cold scenarios.

For some countries where NUTS2 regions show a high potential decrease in production in 2030, an analysis based on CAPRI data (farm type specialisation and farm size) was carried out. The objective of this exercise was to present a methodology that could be used to carry out a comprehensive analysis for the whole EU27 with a higher degree of detail at farming system level.

As an exemplification, this analysis shows that in France, according to the warm climate change scenario for wheat, specialist cereal crops and general field cropping/mixed cropping farming types will be potentially affected by a significant decrease of production in 2030. They concern farms of medium and large size. In Poland, for the same scenario, small size farms specialised in general field cropping/mixed cropping and mixed crops-livestock should be potentially affected.

For sunflower in Hungary the expected potential decrease foreseen by the warm scenario in 2030 will impact specialist cereal, oilseed and protein crops farms of medium and large size.

The Italian example for grain maize shows that according to the 2030 warm scenario, the expected decline in production will potentially affect mixed crops-livestock and, to a small extent, specialist cereal crop farms. The farms involved are generally medium and big size farms. Since mixed crops-livestock farms are also affected, the impact of variation may be higher as these farms could have fewer opportunities to adapt compared to specialist cereal crops farms.

The methodological aspects and the associated assumptions qualify the analysis presented as an exploratory study. The last chapter has added, in perspective, the dimensions and the methodology that could be implemented in order to produce an integrated and transparent multi-level analysis. While some of the key drivers of the analysis of agriculture and climate change require a global perspective and modelling, the analysis of impacts will have to be context-specific and should not be estimated via analyses at a high level of abstraction.

The results of the project should be considered from two main perspectives. Firstly, the impact of the known variability of future climate estimates must be carefully evaluated. The two realizations of the same climate scenario that represents only one of the several possible future greenhouse gases emission scenarios as derived from climate model simulations have shown similar trends with respect to air temperature, but substantial differences in rainfall patterns. There is no screening method to either accept or discard any of the different realizations of climate model predictions, and the estimated scenarios are the state of the art of climate modelling. Such differences have led to, at times, substantially contrasting estimates of crop production in different areas.

In addition to the variability introduced by climate, technological development and management practice add further variability to estimates of future yields. The scope of the current study did not allow considering these two factors so that for the horizons of 2020 and 2030 current technology and management rules have been applied.

Secondly, the study has highlighted the potential vulnerability of some production systems in some areas. It is an estimate of potential vulnerability because of the level of abstraction applied in the analysis, targeted at full coverage of EU27 with a common methodology, and necessarily constrained to the detail of information available during the study and in a foreseeable future. An estimate of actual vulnerability may be produced in a context-specific analysis, at a lower level of abstraction and as articulated in the last chapter of this report. It would be extremely risky to undertake context-specific measures to anticipate and counteract the impact of a given climate estimate from the results of an analysis at the level of abstraction of this study. This limitation, however, cannot be a source of disappointment with respect to this study that has to be considered as a necessary first step in tackling the complexities of agricultural production systems in the extremely diversified regions of Europe. The work done, beyond the first step of the analysis produced, has also set the foundation to progress at a more context specific level, with the needed involvement of knowledge and action of Members States.

The analysis of climate change and agriculture has multiple targets, and new goals can arise in response to the dynamics of the system. The science behind the analysis evolves, and new and updated layers of information will become available, demanding for an operational capacity to update and further specialize assessments. The transparency and at least a partial capability to reproduce this type of analysis by third parties is also key to avoid a biased sampling and to enhance the acceptance of results. The flexibility and the transparency required to provide robust policy support on a very articulated and economically relevant sector like agriculture demand for structural enhancements of the knowledge and modelling platforms currently available at JRC.

References

Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M., 2006. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environmental Science & Policy 9, 101–115.

Acock, B., Acock, M., 1991. Potential for using long-term field research data to develop and validate crop simulators. Agronomy Journal 83, 56–61.

Andersen, E., 2010. Regional typologies of farming systems contexts, SEAMLESS Report No.53, EU 6th Framework Programme, contract no. 010036-2.

Anderson, K., Bows, A., 2011. Beyond "dangerous" climate change: emission scenarios for a new world. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369, 20.

Annetts, J.E., Audsley, E., 2002. Multiple Objective Linear Programming for Environmental Farm Planning. The Journal of the Operational Research Society 53, 933–943.

Armington, P.S., 1986. A Theory of Demand for Products Distinguished by Place of Production. International Monetary Fund Staff Papers 16, 159–176.

Arnell, N.W., Livermore, M.J.L., Kovats, S., Levy, P.E., Nicholls, R., Parry, M.L., Gaffin, S.R., 2004. Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Climate Change 14, 3–20.

Audsley, E., Pearn, K.R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M.D.., Trnka, M., Alexandrov, V., 2006. What can scenario modelling tell us about future European scale agricultural land use, and what not? Environmental Science & Policy 9, 148–162.

Baettig, M.B., Wild, M., Imboden, D.M., 2007. A climate change index: Where climate change may be most prominent in the 21st century. Geophys. Res. Lett. 34, L01705.

Baron, C., Sultan, B., Balme, M., Sarr, B., Traore, S., Lebel, T., Janicot, S., Dingkuhn, M., 2005. From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 2095.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., García-Herrera, R., 2011. The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. Science.

Betts, R.A., 2005. Integrated approaches to climate-crop modelling: needs and challenges. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 2049–2065.

Bojanowski, J., Donatelli, M.,Auto-calibration method of Bristow and Campbell solar radiation model. Environmental Modelling and Software.

Britz, W., Witzke, P., 2008. CAPRI model documentation 2008.

van Bussel, L.G.., Müller, C., van Keulen, H., Ewert, F., Leffelaar, P.A., 2011. The effect of temporal aggregation of weather input data on crop growth models' results. Agricultural and Forest Meteorology 151, 607–619.

Christensen, J., Christensen, O., 2007. A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic Change 81, 7–30.

Christensen, J.H., Boberg, F., Christensen, O.B., Lucas-Picher, P., 2008. On the need for bias correction of regional climate change projections of temperature and precipitation. Geophys. Res. Lett. 35, L20709.

Collins, M., 2007. Ensembles and probabilities: a new era in the prediction of climate change. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365, 1957 –1970.

Collins, M., Tett, S.F.B., Cooper, C., 2001. The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 17, 61–81.

Delworth, T.L., Broccoli, A.J., Rosati, A., Stouffer, R.J., Balaji, V., Beesley, J.A., Cooke, W.F., Dixon, K.W., Dunne, J., Dunne, K.A., Durachta, J.W., Findell, K.L., Ginoux, P., Gnanadesikan, A., Gordon, C.T., Griffies, S.M., Gudgel, R., Harrison, M.J., Held, I.M., Hemler, R.S., Horowitz, L.W., Klein, S.A., Knutson, T.R., Kushner, P.J., Langenhorst, A.R., Lee, H.-C., Lin, S.-J., Lu, J., Malyshev, S.L., Milly, P.C.D., Ramaswamy, V., Russell, J., Schwarzkopf, M.D., Shevliakova, E., Sirutis, J.J., Spelman, M.J., Stern, W.F., Winton, M., Wittenberg, A.T., Wyman, B., Zeng, F., Zhang, R., 2006. GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. Journal of Climate 19, 643–674.

Diffenbaugh, N.S., Giorgi, F., Raymond, L., Bi, X., 2007. Indicators of 21st century socioclimatic exposure. Proceedings of the National Academy of Sciences 104, 20195 –20198.

Donatelli, M., Bellocchi, G., Carlini, L., 2006. Sharing knowledge via software components: Models on reference evapotranspiration. European Journal of Agronomy 24, 186–192.

Donatelli, M., Bellocchi, G., Habyarimana, E., Bregaglio, S., Confalonieri, R., Baruth, B., 2009. CLIMA: a weather generator framework, in: 18th World IMACS Congress and MODSIM09 International Congress on

Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, Cairns, Australia.
Donatelli, M., Confalonieri, R., 2011. Biophysical models for cropping system simulation, in: Flichman, G. (Ed.), Bio-Economic Models Applied to Agricultural Systems. Springer, pp. 59–87.
Donatelli, M., Tubiello, F., Stockle, C.O., Rosenzweig, C., Gristina, L., 1998. Simulating cropping system as affected by climate change and elevated CO_2 in Italy, in: Proc. of the 7th ICCTA Conference. Presented at the ICCTA Conference, Firenze, Italy.
Dosio, A., Paruolo, P., 2011. Bias correction of the ENSEMBLES high-resolution climate change projections for use by impact models: Evaluation on the present climate. J. Geophys. Res. 116, D16106.
Eliasson, A., Jones, R.J.A., Nachtergaele, F., Rossiter, D.G., Terres, J.-M., Van Orshoven, J., van Velthuizen, H., Bottcher, K., Haastrup, P., Le Bas, C., 2010. Common criteria for the redefinition of Intermediate Less Favoured Areas in the European Union. Environmental Science & Policy 13, 766–777.
den Elzen, M.G.J., van Vuuren, D.P., 2007. Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. Proceedings of the National Academy of Sciences 104, 17931–17936.
Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J., Leemans, R., 2005. Future scenarios of European agricultural land use:: I. Estimating changes in crop productivity. Agriculture, Ecosystems & Environment 107, 101–116.
Falloon, P., Betts, R., 2010. Climate impacts on European agriculture and water management in the context of adaptation and mitigation–The importance of an integrated approach. Special Section: Integrating Water and Agricultural Management Under Climate Change 408, 5667–5687.
Fasbender, D., Ouarda, T.B.M.J., 2010. Spatial Bayesian Model for Statistical Downscaling of AOGCM to Minimum and Maximum Daily Temperatures. Journal of Climate 23, 5222–5242.
Fischer, G., Shah, M., N. Tubiello, F., van Velhuizen, H., 2005. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 2067–2083.
Gao, X., Giorgi, F., 2008. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global and Planetary Change 62, 195–209.
Gao, X., Pal, J.S., Giorgi, F., 2006. Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. Geophys. Res. Lett. 33, L03706–.
Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33, L08707.
Giorgi, F., Mearns, L.O., 1991. Approaches to the simulation of regional climate change: A review. Rev. Geophys. 29, 191–216.
Gocht, A., Britz, W., 2011. EU-wide farm type supply models in CAPRI - How to consistently disaggregate sector models into farm type models. Journal of Policy Modeling 33, 146–167.
Gocht, A., Britz, W., Adenäuer, M., Ciaian, P., Gomez y Paloma, S., 2011. Farm level policy scenario analysis. JRC Scientific and Technical Report, European Commission, Joint Research Centre, EUR 24787 EN.
Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., Wiltshire, A., 2010. Implications of climate change for agricultural productivity in the early twenty-first century. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2973.
Hansen, J.W., Challinor, A., Ines, A., Wheeler, T., Moron, V., 2006. Translating climate forecasts into agricultural terms: advances and challenges. Climate Research 33, 27.
Hansen, J.W., Jones, J.W., 2000. Scaling-up crop models for climate variability applications. Agricultural Systems 65, 43–72.
Hazell, P., Norton, R., 1986. Mathematical Programming for Economic Analysis in Agriculture. MacMillan Publishing Company, New York.
Hewitson BC, Crane RG, 1996. Climate downscaling: techniques and application. Clim Res 07, 85–95.
Howitt, E.R., 1995. A calibration method for agricultural economic production models. Journal of Agricultural Economics 46, 147–159.
Ines, A.V.M., Hansen, J.W., 2006. Bias correction of daily GCM rainfall for crop simulation studies. Agricultural and Forest Meteorology 138, 44–53.
IPCC, 2007a. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
IPCC, 2007b. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
Jacob, D., Barring, L., Christensen, O., Christensen, J., de Castro, M., DÃ©quÃ©, M., Giorgi, F., Hagemann, S., Hirschi, M., Jones, R., Kjellstrom, E., Lenderink, G., Rockel, B., SÃ¡nchez, E., Schar, C., Seneviratne, S., Somot, S., van Ulden, A., van den Hurk, B., 2007. An inter-comparison of regional climate models for Europe: model performance in present-day climate. Climatic Change 81, 31–52.
Jaggard, K.W., Qi, A., Ober, E.S., 2010. Possible changes to arable crop yields by 2050. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2835.
Jamieson, P.D., Semenov, M.A., Brooking, I.R., Francis, G.S., 1998. Sirius: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy 8, 161–179.

Janssen, S., Louhichi, K., Kanellopoulos, A., Zander, P., Flichman, G., Hengsdijk, H., Meuter, E., Andersen, E., Belhouchette, H., Blanco, M., Borkowski, N., Heckelei, T., Hecker, M., Li, H., Oude Lansink, A., Stokstad, G., Thorne, P., van Keulen, H., van Ittersum, M., 2010. A Generic Bio-Economic Farm Model for Environmental and Economic Assessment of Agricultural Systems. Environmental Management 46, 862–877.
Jansson, T., Heckelei, T., 2011. Estimating a Primal Model of Regional Crop Supply in the European Union. Journal of Agricultural Economics 62, 137–152.
Johns, T., Royer, J.-F., Höschel, I., Huebener, H., Roeckner, E., Manzini, E., May, W., Dufresne, J.-L., Otter\a, O., van Vuuren, D., Salas y Melia, D., Giorgetta, M., Denvil, S., Yang, S., Fogli, P., Körper, J., Tjiputra, J., Stehfest, E., Hewitt, C., 2011. Climate change under aggressive mitigation: the ENSEMBLES multi-model experiment. Climate Dynamics 1–29.
Jongman, R., Bunce, R., Metzger, M., Mucher, C., Howard, D., Mateus, V., 2006. Objectives and Applications of a Statistical Environmental Stratification of Europe. Landscape Ecology 21, 409–419.
Kanellopoulos, A., Hengsdijk, H., Janssen, S., van Ittersum, M.K., 2009. Ex-624 ante assessment of the abolishment of the EU set aside policy: Results from a bio-economic farm analysis., in: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP 2009). Wageningen University and Research Centre, Wageningen, Egmond aan Zee, The Netherlands, 10-12 March 2009, pp. 478–479.
Louhichi, K., Belhouchette, H., Wery, J., Therond, O., Flichman, G., Casellas, E., 2008. Application of FSSIM in two Test Case regions to assess agro-environmental policies at farm and regional level, PD 6.3.2.2, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2, www.SEAMLESS-IP.org.
Louhichi, K., Hengsdijk, H., Janssen, S., Bigot, G., Perret, E., 2009. EU dairy farming in the face of change: An exploration using a bio-economic farm model, in: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP 2009). Wageningen University and Research Centre, Wageningen, Egmond aan Zee, The Netherlands, 10-12 March 2009, pp. 262–263.
Louhichi, K., Janssen, S., Kanellopoulos, A., Li, H., Borkowski, N., Flichman, G., Hengsdijk, H., Zander, P., Blanco, M., Stokstad, G., Athanasiadis, I., Rizzoli, A.E., Huber, D., Heckelei, T., van Ittersum, M.K., 2010. A generic Farming System Simulator. Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessmen, in: Brouwer, F., van Ittersum, M.K. (Eds.), Environmental and Agricultural Modelling: Integrated Approaches for Policy Impact Assessmen. Springer Academic Publishing.
Louhichi, K., Kanellopoulos, A., Janssen, S., Flichman, G., Blanco, M., Hengsdijk, H., Heckelei, T., Berentsen, P., Lansink, A.O., Ittersum, M.V., 2010. FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. Agricultural Systems 103, 585–597.
Majewski, E., Was, A., Belhouchette, H., Louhichi, K., Mouratiadou, I., 2009. Impact Assessment of policy changes on the arable sector using the FSSIM model: case study of the Zachodniopomorskie NUTS region., in: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP 2009). Wageningen University and Research Centre, Wageningen, Egmond aan Zee, The Netherlands, 10-12 March 2009, pp. 484–485.
Maracchi, G., Sirotenko, O., Bindi, M., 2005. Impacts of Present and Future Climate Variability on Agriculture and Forestry in the Temperate Regions: Europe. Climatic Change 70, 117–135.
Mayr, T.R., Rounsevell, M.D.A., Loveland, P.J., Simota, C., 1996. Agro-climatic change and european soil suitability : Regional modelling at monthly time-steps. International agrophysics 10, 155–170.
Mearns, L.O., Easterling, W., Hays, C., Marx, D., 2001. Comparison of Agricultural Impacts of Climate Change Calculated from High and Low Resolution Climate Change Scenarios: Part I. The Uncertainty Due to Spatial Scale. Climatic Change 51, 131–172.
Mearns, L.O., Rosenzweig, C., Goldberg, R., 1996. The effect of changes in daily and interannual climatic variability on CERES-Wheat: A sensitivity study. Climatic Change 32, 257–292.
Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Macher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Global Ecology and Biogeography 14, 549–563.
Moriondo, M., Giannakopoulos, C., Bindi, M., 2011. Climate change impact assessment: the role of climate extremes in crop yield simulation. Climatic Change 104, 679–701.
Mouratiadou, I., Russell, G., Topp, C., Louhichi, K., Moran, D., 2010. Modelling Common Agricultural Policy-Water Framework Directive interactions and cost-effectiveness of measures to reduce nitrogen pollution. Water Science & Technology 61, 2689–2697.
Murphy, J., 1999. An Evaluation of Statistical and Dynamical Techniques for Downscaling Local Climate. Journal of Climate 12, 2256–2284.
Nakićenović, N., Alcamo, J., Davis, G., De Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Gr\übler, A., Jung, T.Y., Kram, T., others, 2000. IPCC Special Report on Emissions Scenarios (SRES). Cambridge: Cambridge University Press.
Nelson, G.C., Rosengrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M., Lee, D., 2009. Climate Change: Impact on agriculture and costs of adaptation. International Food Policy Research Institute.

Olesen, J., Carter, T., Díaz-Ambrona, C., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M., Morales, P., Palutikof, J., Quemada, M., Ruiz-Ramos, M., Rubæk, G., Sau, F., Smith, B., Sykes, M., 2007. Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Climatic Change 81, 123–143.
Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. European Journal of Agronomy 16, 239–262.
Olesen, J.E., Petersen, B.M., Berntsen, J., Hansen, S., Jamieson, P.D., Thomsen, A.G., 2002. Comparison of methods for simulating effects of nitrogen on green area index and dry matter growth in winter wheat. Field Crops Research 74, 131–149.
Osborn, T.J., Hulme, M., 1997. Development of a Relationship between Station and Grid-Box Rainday Frequencies for Climate Model Evaluation. Journal of Climate 10, 1885–1908.
Osborne, T.M., Lawrence, D.M., Challinor, A.J., Slingo, J.M., Wheeler, T.R., 2007. Development and assessment of a coupled crop–climate model. Global Change Biology 13, 169–183.
Paeth, H., Scholten, A., Friederichs, P., Hense, A., 2008. Uncertainties in climate change prediction: El Niño-Southern Oscillation and monsoons. Global and Planetary Change 60, 265–288.
Parker, W.S., 2010. Predicting weather and climate: Uncertainty, ensembles and probability. Special Issue: Modelling and Simulation in the Atmospheric and Climate Sciences 41, 263–272.
Parry, M., Rosenzweig, C., Livermore, M., 2005. Climate change, global food supply and risk of hunger. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 2125–2138.
Piani, C., Weedon, G.P., Best, M., Gomes, S.M., Viterbo, P., Hagemann, S., Haerter, J.O., 2010. Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. Journal of Hydrology 395, 199–215.
Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philosophical Transactions of the Royal Society B: Biological Sciences 360, 2021.
Reidsma, P., Ewert, F., Boogaard, H., Diepen, K. van, 2009. Regional crop modelling in Europe: The impact of climatic conditions and farm characteristics on maize yields. Agricultural Systems 100, 51–60.
Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., Tompkins, A., 2003. The atmospheric general circulation model ECHAM 5. PART I: Model description. Max-Planck-Institute for Meteorology.
Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., Imeson, A., 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453, 353–357.
Rounsevell, M.D.A., Ewert, F., Reginster, I., Leemans, R., Carter, T.R., 2005. Future scenarios of European agricultural land use:: II. Projecting changes in cropland and grassland. Agriculture, Ecosystems & Environment 107, 117–135.
Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J., others, 2006. A coherent set of future land use change scenarios for Europe. Agriculture, Ecosystems & Environment 114, 57–68.
Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427, 332–336.
Schneider, S., Easterling, W., Mearns, L.O., 2000. Adaptation: Essential to impact assessment but still highly subjective. Climate Change 45, 203–221.
Semenov, M.A., Barrow, E.M., 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change 35, 397–414.
Semenov, M.A., Porter, J.R., 1995. Climatic variability and the modelling of crop yields. Biospheric Aspects of the Hydrological Cycle 73, 265–283.
Semenov, M.A., Stratonovitch, P., 2010. Use of multi-model ensembles from global climate models for assessment of climate change impacts. Clim. Res. 41, 1–14.
Semenov MA, Donatelli M, Stratonovitch P, Chatzidaki E, Baruth B, 2010. ELPIS: a dataset of local-scale daily climate scenarios for Europe. Clim Res 44, 3–15.
Stöckle, C., Nelson, R., Donatelli, M., Castellvi, F., 2001. ClimGen: a flexible weather generation program, in: 2nd International Symposium Modelling Cropping Systems. Florence, Italy. pp. 16–18.
Stockle, C.O., Martin, S.A., Campbell, G.S., 1994. CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yield. Agricultural Systems 46, 335–359.
Teutschbein, C., Seibert, J., 2010. Regional Climate Models for Hydrological Impact Studies at the Catchment Scale: A Review of Recent Modeling Strategies. Geography Compass 4, 834–860.
Traoré, B., Louhichi, K., Rapidel, B., 2009. A bio-economic model to analyse the performance of the cotton sector in Mali., in: Proceedings of the Conference on Integrated Assessment of Agriculture and Sustainable Development Setting the Agenda of Science and Policy (AgSAP 2009). Wageningen University and Research Centre, Wageningen, Egmond aan Zee, The Netherlands, 10-12 March 2009, pp. 276–277.
Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvag, A.O., Eitzinger, J., Seguin, B., Peltonen-sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovsky, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vucetic, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V.,

Semerádová, D., Zalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Global Change Biology.

Tubiello, F.N., Donatelli, M., Rosenzweig, C., Stockle, C.O., 2000. Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy 13, 179–189.

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. European Journal of Agronomy 18, 57–74.

Wilby, R.L., Wigley, T.M.L., Conway, D., Jones, P.D., Hewitson, B.C., Main, J., Wilks, D.S., 1998. Statistical downscaling of general circulation model output: A comparison of methods. Water Resour. Res. 34, 2995–3008.

Wilks, D.S., 1992. Adapting stochastic weather generation algorithms for climate change studies. Climatic Change 22, 67–84.

Glossary

Adaptation
Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007) expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007)

APES
Agricultural Production and Externalities Simulator. A modular simulation systems at the origin of the model layer of the BioMA framework.

AOGCM
Atmosphere-**O**cean **G**eneral **C**irculation **M**odels. A coupling of atmospheric and oceanic general circulation models, representing the pinnacle of complexity in climate models, internalising as many processes as possible. They are often referred to simply as GCMs (General Circulation Models).

ASEMARS
Actions in Support of the Enlargement of the MARS Crop Yield Forecasting System

A1B
An emission scenario proposed in the SRES describing a globalised, economically-oriented world with a balanced emphasis on all energy sources. This is the emission scenario considered in AVEMAC.

BioMA
Biophysical **M**odel **A**pplications. A software platform developed at JRC for running biophysical models on generic spatial units.

Bio-physical model
Algorithms to simulate a part of the biophysical system. Models are typically coded into components.

CAPRI FARM
Farm specialization dataset based on CAPRI (Common Agricultural Policy Regionalized Impact) database

CGMS
Crop **G**rowth **M**onitoring **S**ystem. The CGMS is the combination of the WOFOST crop growth model, a relational database and a statistical yield prediction module. From 2004 onwards the development of CGMS continued in the framework of the MARSOP2, ASEMARS and MARSOP3 projects, leading to the current version CGMS 10.0.3.2.

Climate change
Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.

ClimGen
A weather generator used in AVEMAC.

CROPSyst
Cropping **Syst**ems simulation model. A process-based model generic simulator for crops. Different crops can be simulated using appropriate parameters.

ECHAM5
ECHAM5 is a GCM developed at the Max Planck Institute for Meteorology in Germany. One of the major models used in the reports of the IPCC. In the context of AVEMAC, ECHAM5 is further used as a simplified abbreviation of DMI-HIRHAM5-ECHAM5, the ECHAM5 GCM coupled with the HIRHAM5 RCM in the framework of the ENSEMBLES project and later bias-corrected by Dosio & Paruolo (2011). In the AVEMAC study frame (Europe from 2000 till 2030), ECHAM5 provides a generally colder realization of an emission scenario with respect to the rest of the models in ENSEMBLES.

ECMWF
European **C**entre for **M**edium-Range **W**eather **F**orecasts. Intergovernmental organisation supported by 32 States that provide operational medium- and extended-range forecasts.

ENSEMBLES
The ENSEMBLES project produced probabilistic projections of European climate to help inform researchers, decision makers, businesses and the public with climate information from the latest climate modelling and analysis tools. The main objective of ENSEMBLES was to allow uncertainty in climate change models to be measured. ENSEMBLES was financed by the Sixth Framework Programme.

ESTAT
Eurostat

GCM
A **G**eneral **C**irculation **M**odel (GCM) is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on equations for a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). These equations are the basis for simulating the atmosphere or ocean of the Earth. Atmospheric and Oceanic GCMs (AGCM and OGCM) are key components of Global Climate Models along with sea ice and land-surface components. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change See also AOGCM.

GHG
Green**H**ouse**G**as. A gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect.

HadCM3
Hadley **C**entre **C**oupled **M**odel, version **3**. A GCM developed at the Hadley Centre in the United Kingdom. One of the major models used in the reports of the IPCC. In the context of AVEMAC, HadCM3 is further used as a simplified abbreviation of METO-HC-HadRM3Q0-HadCM3Q0, the HadCM3 GCM coupled with the HadRM3 RCM in the framework of the ENSEMBLES project and later bias-corrected by Dosio & Paruolo (2011). In the AVEMAC study frame (Europe from 2000 till 2030), HadCM3 provides a generally warmer realization of an emission scenario with respect to the rest of the models in ENSEMBLES.

IPCC
Intergovernmental **P**anel on **C**limate **C**hange. A scientific intergovernmental body which provides comprehensive assessments of current scientific, technical and socio-economic information worldwide about the risk of climate change caused by human activity, its potential environmental and socio-economic consequences, and possible options for adapting to these consequences or mitigating the effects.

JRC
Joint **R**esearch **C**entre

LFA
Less **F**avoured **A**reas. A broad mechanism in the European Union for improving the viability of agriculture in areas with natural handicaps.

MARS
Monitoring **A**gricultural **R**esource**S**. The MARS unit of the Institute for Environment and Sustainability within the European Commission Joint Research Centre provides scientific and technical support on EU Agriculture and Food Security policies. In Europe, the Unit addresses key issues related to the management and control of the Common Agriculture Policy: Independent crop yield forecasts, agricultural insurances, standard control methods of area based subsidies, compliance with environment, and effect of climate change. It supports EU projects related to Land Administration, the enlargement process, and the GMES Space Component. In developing countries, assistance is given to the EU Food Security Thematic Program with special emphasis on Africa, and to providing building blocks for an European capacity for Global Agriculture Monitoring. The activities of the Unit are based on expertise in agro- meteorological crop modelling, sampling methods, econometric, geomatics (GIS, GPS and ICT), and satellite & airborne remote-sensing (the Unit manages the EC Framework Contracts for the provision of Satellite Remote Sensing data and manages the access/dissemination of EU image data archives).

MCYFS
MARS **C**rop **Y**ield **F**orecasting **S**ystem

Modelling solution
A composition of models built for a specific purpose. For instance, a "crop model" capable to simulate water limited production is a modelling solution composed of models for crop development and growth, and for soil water such "sub-models" can be implemented in the same discrete software unit, or in separate software components.

NUTS
The **N**omenclature des **U**nités **T**erritoriales **S**tatistiques or **N**omenclature of **U**nits for **T**erritorial **S**tatistics is a standard developed and regulated by the European Union for referencing the subdivisions of its member states.

RCM
Regional **C**limate **M**odel. A climate model with a focus on a region (such as a continent like Europe), which is typically driven by initial and boundary conditions supplied by a GCM. RCM have a higher spatial resolution than GCM and can integrate different processes, such as those linked to topography, which are only relevant at this higher spatial resolution.

SEAMLESS
System for Environmental and Agricultural Modelling: Linking European Science and Policy

Software component
A unit of composition with contractually specified interfaces and explicit context dependencies only. A software component can be deployed independently and is subject by composition by third parties.

SRES
Special Report on Emission Scenarios. A report prepared by the IPCC which describes emission scenarios to make projections of possible future climate change. The SRES divided emission scenarios in four categories along two axes: whether the future is either more globalised or regionalised, and whether it will be more environmentally or economically centred.

UAA
Utilized **A**gricultural **A**rea.

WARM
Water **A**ccounting **R**ice **M**odel used for simulating rice growth

Weather generator
Algorithms capable of generating synthetic time series of weather data based on a stochastic procedure and observed weather time series. The resulting simulated weather time-series have the same statistical properties as the observed calibration data.

WOFOST
WOrld**FO**od**ST**udies is a simulation model for the quantitative analysis of the growth and production of annual field crops. It is a mechanistic model that explains crop growth on the basis of the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions.

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Abstract
This final report of the AVEMAC study presents an assessment of the potential vulnerability of European agriculture to changing climatic conditions in the coming decades. The analysis is based on weather data generated from two contrasting realizations of the A1B emission scenario of the Intergovernmental Panel on Climate Change (IPCC) for the time horizons 2020 and 2030. These two realizations (obtained from two different general circulation models, downscaled using regional climate models and bias-corrected) represent the warmest and coldest realizations of the A1B scenario over Europe as estimated by the ENSEMBLES project. The future weather data fed two types of analyses. The first analysis consisted in computing static agro-meteorological indicators as proxies of potential vulnerabilities of agricultural systems, expressed as changes in the classification of agricultural areas in Europe under climate constraints. The second analysis relied on biophysical modelling to characterize crop specific plant responses derived from crop growth simulations at different production levels (potential production, water-limited production, and production limited by diseases). Assessing the importance of vulnerability to climate change requires not only the localisation of relative yield changes, but also the analysis of the impact of the change on the acreage affected. Consequently, the simulation results of the impact assessment on crops were further processed to estimate the potential changes in production at sub-national (NUTS2) level. This was achieved by relating the simulation results to farm typologies in order to identify which types of systems are likely to be affected by reductions in production. The analyses of this study must be considered as a first step only, since they have neither included adaptation strategies that the farmer can take in response to changes in climate, nor a bio-economic evaluation of estimated vulnerabilities. Therefore, the main aspects and the requirements for a possible future integrated analysis at EU27 level to address climate change and agriculture with the target of providing policy support are also presented in this report. Eventually the results of this study shall help the formulation of appropriate policy options and the development of adequate policy instruments to support the adaptation to climate change of the EU agricultural sector.

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