Assessing the adaptive capacity of agriculture in the Netherlands to the impacts of climate change under different market and policy scenarios (AgriAdapt)

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Scenario development and assessment of the potential impacts of climate and market changes on crops in Europe

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climate changes spatial planning

1. Introduction and objectives of the report

The Netherlands is an important producer and exporter of agricultural products. Changes in climate, markets and policies may have a large impact on the agricultural sector and farmers will need to adapt to these changes. Sector and policy documents have, so far, insufficiently considered the impacts of climate change and increased climate variability on the sector.

Originally, climate impact studies have, with a few exceptions (e.g. Rötter & van Diepen, 1994), focused on biophysical relationships explaining the potential impacts of climate change on primary production (Rosenzweig and Parry, 1994; Downing et al., 2000; Reilly et al., 2003). In recent years the importance of socio-economic developments is increasingly recognised and considered in climate impact assessments for agriculture (Parry et al., 2004; Fischer et al., 2005; IPCC, 2007). Also, the importance of management and technology development (Ewert et al., 2005) for agricultural production has been stressed.

Of particular importance is the scale at which impact and adaptation options are assessed. Clearly, not only the sensitivity to climate change will differ depending on whether individual farmers, regions or countries are analysed but also the strategies to adapt to these impacts. Scale dependency of adaptation strategies has been reported earlier (Reidsma and Ewert, 2008, Reidsma et al., 2007, 2009, 2010). As shown for regions in southern Europe, individual farms may be vulnerable to climate change but the region as a whole may be not which can be a result of high diversification of farming systems (Reidsma and Ewert, 2008).

Importantly, there may also be feedback mechanisms of large scale responses to global change (e.g. at country or continental level) which may have severe implications at smaller scale (local farm or farm types in a region) affecting the ability of farms or regions to adapt to climate change.

However, scale interactions have hardly been considered in climate change impact assessment studies. Most studies assess impacts at one level of the organization only. Recently, the competitiveness of Dutch agriculture under climate and market change has been assessed. Adaptation in agricultural production was assumed to depend on the economic size of the farms within a sector, with larger farms being less vulnerable than smaller farms (Hermans et al., 2010). The study suggested that changes in Dutch agriculture will depend on productivity change in other EU regions.

Despite the new insights provided there were some limitations in this study (Hermans et al., 2010) which required further attention. The assessment was restricted to wheat, potato and milk production (relying on grass) only and did not assess effects of climate variability. Also, it was not intended to link large scale changes in agricultural production to small scale impacts and adaptation options.

Accordingly, the present project aims to assess potential climate change impacts on agriculture in Europe l in combination with market changes. The specific aim of the present report is to develop scenarios and provide estimations of changes in crop productivity and commodity prices for important crops in Europe as affected by climate change and changes in market drivers such as GDP and population growth. In more detail the objectives of this report are:

- To describe the modelling of crop productivity as affected by climate change, CO2 and technology development. Specific emphasis is on methods of model calibration to improve estimations of the spatio-temperal variability of crop productivity
- To describe the general methodology used to develop scenarios of yield and price changes for crops in Europe
- To describe the considered scenarios for climate change, CO2 and technology development
- To describe the development of scenarios for key drivers of market change
- To present the scenarios for changes in the productivity of and prices for crops in Europe

2. Methods and data

2.1. Description of models and data used

2.1.1. General description

Two models were used and are described in the following sections, i.e. ACE and CAPRI (Britz and Witzke, 2008).
The data we used can be categorized in two types: data for model calibration (crop phenology, soil and yields) and climate data for the simulation of yields in Europe representing different future climate change scenarios.

2.1.2. Description and calibration of ACE-FAST

2.1.2.1. Model description

The crop modeling activities are based on the crop model LINTUL2 for potential and water-limited conditions (Spitters and Schapendonk, 1990; Farré *et al*., 2000; van Ittersum *et al*., 2003) integrated in ACE (Analysing Cropping systems and Environment) a further development of the recently developed cropping system modelling framework APES (Agricultural Production and Externalities Simulator) (van Ittersum *et al*., 2008; Donatelli *et al*., 2010) which follows the principles of modularity (Hillyer *et al*., 2003). LINTUL2 was further extended with a calibration algorithm and implemented to allow fast simulations for large numbers of spatial units and years with more than 100000 simulations runs per scenario (i.e. 8^3 times 100000 for the calibration runs) for which temporal model performance becomes a critical issue. The resulting model FAST (Fast Agro-Simulation Technique) implemented in ACE (ACE-FAST) is used for the simulations in this study.

LINTUL2 considers effects of climate including limited water supply as described in (Spitters and Schapendonk, 1990; Farré *et al*., 2000) and has been used in numerous climate change studies (e.g. Ewert *et al*., 1999; van Oijen and Ewert, 1999; Wolf and van Oijen, 2002). Different to other model versions (Ewert *et al*., 1999; van Oijen and Ewert, 1999; Rodriguez *et al*., 2001; Wolf and van Oijen, 2002) for the present study a simple representation of the effects of increased atmospheric CO_2 concentration (denoted as [CO_2]) on biomass production was considered using the relationship between [CO_2] and radiation use efficiency as proposed by Stockle *et al*., (1992):

$$RUE = (100)([CO_2])/[-[CO_2] + b_l \exp(-b_2 [CO_2])] \qquad (1)$$

where RUE is Radiation use efficiency in g MJ^{-1} and [CO_2] represents the atmospheric [CO_2] in ppm. The values assigned to the parameters b_l and b_2 are 6928 and 0.0014 respectively, and correspond to a moderate increase of RUE due to atmospheric [CO_2] elevation from 350 to 600 ppm (Stockle *et al*., 1992). This relationship was assumed or all crops except for grain maize which is a C4 plant and presents no (≤1%) stimulation of photosynthesis at elevated (≥600 ppm) atmospheric [CO_2] (Leakey, 2009).The second effect of [CO_2] on biomass production is to reduce crop transpiration. A linear diminution of transpiration up to 10% for all crops was taken into consideration when the atmospheric [CO_2] reaches 700 ppm (Ewert *et al*., 2002, Kruijt *et al*., 2008).

2.1.2.2. Data for model run

2.1.2.2.1. Weather data

Weather data were obtained from the SEAMLESS database (van Ittersum et al., 2008; Janssen et al., 2009) for 533 climate zones in EU25 (Janssen et al., 2009; Andersen et al., 2010) for the period 1983-2006. A climate zone is spatial unit that conmbines NUTS-2 (Nomenclature of Territorial Units for Statistics) regions and Environmental Zones (EnZ) (Metzger et al., 2005). Data included daily rainfall (mm/ d-1), maximum air temperature (°C), minimum air temperature (°C), global solar radiation (MJ/ m2-2 d-1), wind speed (m/ s-1) and vapour pressure (hPa). Evapotranspiration (mm/ day-1), was available from the observed database where it was calculated with the Penman formula from temperature, wind speed and vapour pressure (Allen et al., 1998).

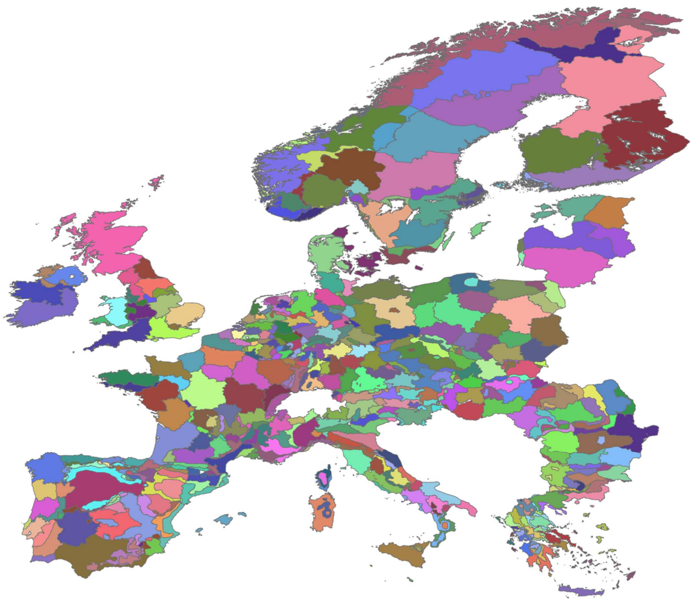

Figure 1. Climate zones in Europe for which daily weather data are available

2.1.2.2.2. Soil data

Soil characteristics at the level of AgriEnvironmental Zones (AEnZ) (Hazeu et al., 2010), a further refinement of the climatic zones were also available from the Pan European SEAMLESS database (van Ittersum et al., 2008; Andersen et al., 2010). Six different soil types were defined according to topsoil organic carbon levels (Hazeu et al., 2010). However, in this study only the dominant soil type per AEnZ, i.e. the soil type covering the largest area in each AeNZ, was considered and aggregated to the level of NUTS-2 (Nomenclature of Territorial Units for Statistics) administrative regions for which yield statistics were also available.

2.1.2.2.3. Crop data

Crop phenology

Yearly sowing and harvest dates for grain maize, potatoes, sugar beet, winter barley and winter wheat were obtained from the JRC/MARS Crop Knowledge Base for 233 NUTS-2 regions across Europe (JRC, 1998). However, due to missing values in some NUT2 regions and years, these dates were averaged to the level of 13 Environmental Zones (EnZ) across Europe (Metzger et al., 2005). Subsequently, the obtained sowing and harvest dates for the 13 EnZs were disaggregated again to the climate zones. These data of sowing and harvest dates were then used for the calibration of ACE-FAST.

Crop yields
Yearly yields were available for NUTS-2 regions from 1983 to 2006 from the EUROSTAT database (EUROSTAT, 2010). For Germany, data gaps were noticed and filled with data from the Federal Office of Statistics of Germany (DESTATIS, 2010). The yield data were the basis for the calibration exercise of ACE-FAST.

2.1.2.3. Model calibration

2.1.2.3.1. Calibration criteria

ACE-FAST uses an optimization brute-force search algorithm for the calibration of crop phenology and three biomass production parameters and the yield correction factor. The targeted parameters were determined by the minimum root mean square error RMSE between simulated and observed data given by:

$$\mathrm{RMSE}(\theta_s - \theta_o) = \sqrt{\frac{\sum_{i=1}^{n}(x_{\mathrm{s},i} - x_{\mathrm{o},i})^2}{n}} \quad (2)$$

where *s* is simulated and *o* is observed yield, θ is a yield data vector and *x* is a yield data point. The calibration algorithm was set up to search for the best value for each considered parameter (i.e. minimising RMSE) within a maximum of eight iterations. Tests have shown that larger numbers of search iterations improve parameter values only marginally.

2.1.2.3.2. Calibration procedure and methods

Before applying ACE-FAST for projecting climate change impacts in Europe we tested the effect of three different calibration methods to identify the most suitable method. The methods tested were;

(1) Region-specific calibration of phenology parameters only,
(2) Region-specific calibration of phenology parameters and a correction factor for yield estimations.
(3) Region-specific calibration of phenology and selected growth parameters instead of a yield correction factor

Calibration of phenology parameters
For all three calibration methods phenology parameters were calibrated as follows. Temperature sums for the 533 climate zones of EU25 were calculated using the observed and aggregated crop phenology data for the stages sowing and maturity, and the historical weather data at climate zones level. As a result one set of phenology parameters (temperature sums) was provided for each climate zone. Growth parameters and yield were not calibrated and one growth parameter set was used for all regions across Europe.

Calculation of yield correction factors
This method considers calibration of phenology parameters combined with the calculation and use of a yield correction factor. Available yields statistics were de-trended to exclude yield increases resulting from technology development for which no calibration was performed but which was explicitly considered in the scenario analysis. No calibration of growth parameters was performed and one set of growth parameters was used for all regions in Europe. The yield correction factor was calculated for each climate zone based on minimising RMSE between observed and simulated yields from 1983 until 2006. Thus, for each climate zone one yield correction factor was calculated and applied to all years in this climate zone.

Calibration of growth parameters
Selected growth parameters were calibrated using observed crop yields from 1983-2006 which were de-trended as described above for the yield correction factor. The calibration referred to three parameters; (i) radiation use efficiency, (ii) specific leaf area and (iii) drought tolerance. It was assumed that these parameters represent main variety differences in leaf area index and thus light capturing, light conversation and drought sensitivity. As the calibration algorithm allowed for 8 search iterations for each parameter starting from a default value, calibrating 3 parameters simultaneously resulted in 8^3 combinations. The parameter combination with the lowest RMSE of yield simulations for the 24 years (1983-2006) was considered for further simulations. No yield correction factor was considered in this method. Thus, instead of a yield correction factor, one set of growth parameters was provided for each climate zone that was applied to all years in this climate zone.

Depending on the comparison of these different calibration methods (see section 3.1), parameters derived from the best performing method will be used to assess the impacts of climate change and technology development on crops.

2.1.3. Simulations runs of ACE-FAST

The calibrated model ACE-FAST was used to simulate five annual crops, i.e. winter wheat, winter barley, potato, sugar beet and grain maize for Europe (EU-25) for the baseline period from 1983 to 2006. Future crop yields were simulated for the 24 years period centred around 2050 (2041-2064) for the 7 climate change scenarios described above. In order to analyze separately the effects of climate, increased atmospheric [CO_2] and technology development, each scenario was run in three steps. First, simulations considered the influence of climate change on yields only. The next step included also the effect of increased [CO_2]. Finally, in the third step, the influence of technology development (see section 2.2.4) was considered in addition to the effects of climate change and increased [CO_2]. Simulations of the last step were used as inputs into CAPRI.

2.1.4. Description and calibration of CAPRI

2.1.4.1. Model description

The CAPRI modelling system consists of specific databases, a methodology, its software implementation, and the researchers involved in their development, maintenance and applications.

The economic model is split into two major modules. The *supply module* consists of independent aggregate non-linear programming models representing activities of all farmers at regional or farm type level captured by the Economic Accounts for Agriculture. The programming models are a kind of hybrid approach, as they combine a Leontief-technology for variable costs covering a low and high yield variant for the different production activities with a non-linear cost function which captures the effects of labour and capital on farmers' decisions. The non-linear cost function allows for perfect calibration of the models and a smooth simulation response rooted in observed behaviour. The models capture in high detail the premiums paid under CAP, include NPK balances and a module with feeding activities covering nutrient requirements of animals. Main constraints outside the feed block are arable and grassland, set-aside obligations and milk quotas. The complex sugar quota regime is captured by a component maximising expected utility from stochastic revenues. Prices are exogenous in the supply module and provided by the market module. Grass, silage and manure are assumed to be non-tradable and receive internal prices based on their substitution value and opportunity costs.

The market module consists of two sub-modules. The sub-module *for marketable agricultural outputs is a spatial, non-stochastic global multi-commodity* model for about 40 primary and processed agricultural products, covering about 40 countries or country blocks in 27 trading blocks. Bi-lateral trade flows and attached prices are modelled based on the Armington assumptions. The behavioural functions for supply, feed, processing and human consumption apply flexible functional forms where calibration algorithms ensure full compliance with micro-economic theory including curvature. The parameters are synthetic, i.e. to a large extent taken from the literature and other modelling systems. Policy instruments cover Product Support Equivalents and Consumer Support Equivalents (PSE/CSE) from the OECD, (bi-lateral) tariffs, the Tariff Rate Quota (TRQ) mechanism and, for the EU, intervention stocks and subsidized exports. This sub-module delivers prices used in the supply module and allows for market analysis at global, EU and national scale, including a welfare analysis. A second sub-module deals with prices for young animals.

As the supply models are solved independently at fixed prices, *the link between the supply and market modules* is based on an iterative procedure. After each iteration, during which the supply module works with fixed prices, the constant terms of the behavioural functions for supply and feed demand are calibrated to the results of the regional aggregate programming models aggregated to Member State level. Solving the market modules then delivers new prices. A weighted average of the prices from past iterations then defines the prices used in the next iteration of the supply module. Equally, in between iterations, CAP premiums are re-calculated to ensure compliance with national ceilings.

Post-model analysis includes the calculation of different income indicators as variable costs, revenues, gross margins, etc., both for individual production activities as for regions, according to the methodology of the EAA. A welfare analysis at Member State level, or globally, at country or country block level, covers agricultural profits, tariff revenues, outlays for domestic supports and the money metric measure to capture welfare effects on consumers. Outlays under the first pillar of the CAP are modelled in very high detail. Environmental indicators cover NPK balances and output of climate relevant gases according the guidelines of the Intergovernmental Panel on Climate Change (IPCC). Model results are presented as *interactive maps* and as thematic *interactive drill-down tables*.

The *technical solution* of CAPRI is centred on the modelling language GAMS which is applied for most of the data base work and CONOPT applied as solver for the different constrained (optimisation) problems. The different modules are steered by a Graphical User Interface currently realised in C, which interacts with FORTRAN code and libraries which are inter-alias dealing with data base management. Typically, these applications generate run-specific parts of the GAMS code. Exploitation tools apply additionally Java applets for interactive maps and XLM/XSLT to generate interactive HTML tables. A detailed documentation of the CAPRI modelling system can be found in Britz and Witzke (2008).

2.1.4.2. Data for model run

The databases exploit wherever possible *well-documented, official and harmonised data sources*, especially data from EUROSTAT, FAOSTAT, OECD and extractions from the Farm Accounting Data Network (FADN)[1] Specific modules ensure that the data used in CAPRI are mutually compatible and complete in time and space. They cover about 50 agricultural primary and processed products for the EU (see Britz and Witzke, 2008), from farm type to global scale including input and output coefficients.

[1] FADN data are used in the context of so-called study contracts with DG-AGRI, which define explicitly the scope for which the data can be used, who has access to the data and ensure the data are destroyed after the lifetime of the contract.

The economic model builds on a *philosophy of model templates* which are structurally identical so that instances for products and regions are generated by populating the template with specific parameter sets. This approach ensures comparability of results across products, activities and regions, allows for low cost system maintenance and enables its integration within a large modelling network such as SEAMLESS. At the same time, the approach opens up the chance for complementary approaches at different levels, which may shed light on different aspects not covered by CAPRI or help to learn about possibility aggregation errors in CAPRI.

2.1.4.3. Model calibration

The calibration philosophy is twofold. First all parameters steering the model response are based on past observation as much as possible. For example the supply response of each regional farm (on Nuts2 level) is estimated using time series data on land use and corresponding price and cost developments (Jansson, 2007). Similar procedures calibrate the demand and processing behavior as well as the supply functions for regions outside the EU. Whenever estimations on time series were not taken from parameters - like elasticities – they are “borrowed” from other modeling systems.

On top of these parameter estimations, the whole model is calibrated to reproduce an exact point in time, like a base year. It must be understood that the CAPRI simulation engine is not able to simulate over time. However, the model can be calibrated to a point in the future, which is generated by trend estimation and expert information. We call this point in time baseline (which is different to the understanding of this term in the APES-context). For the year 2050, which is our simulation year in this study, this point in time is mainly influenced by projections of the FAO and the IMPACT modeling system who have some experience in long term projections.
A comparison of the resulting crop yields with those simulated by APES has shown, that the CAPRI 2050 baseline is close to the B1.1 scenario (BCCR_BCM2_0/SRES B1 - less warming consistent across all European regions and seasons). Therefore, it was decided to assume that the CAPRI baseline represents the B1.1 situation. All scenario parameters are defined relative to this scenario.

2.2. Scenario development

2.2.1. Overall method for scenario development

The method used for scenario development is summarized in figure 2 and is described in more detail in the following sections. Briefly, future crop yields in Europe considering the effects of climate change and technology development are simulated with ACE-FAST. The projected yield changes are then considered in CAPRI together with scenario dependent assumptions about changes in global drivers (e.g. population and GDP) and climate induced changes in global crop yields.

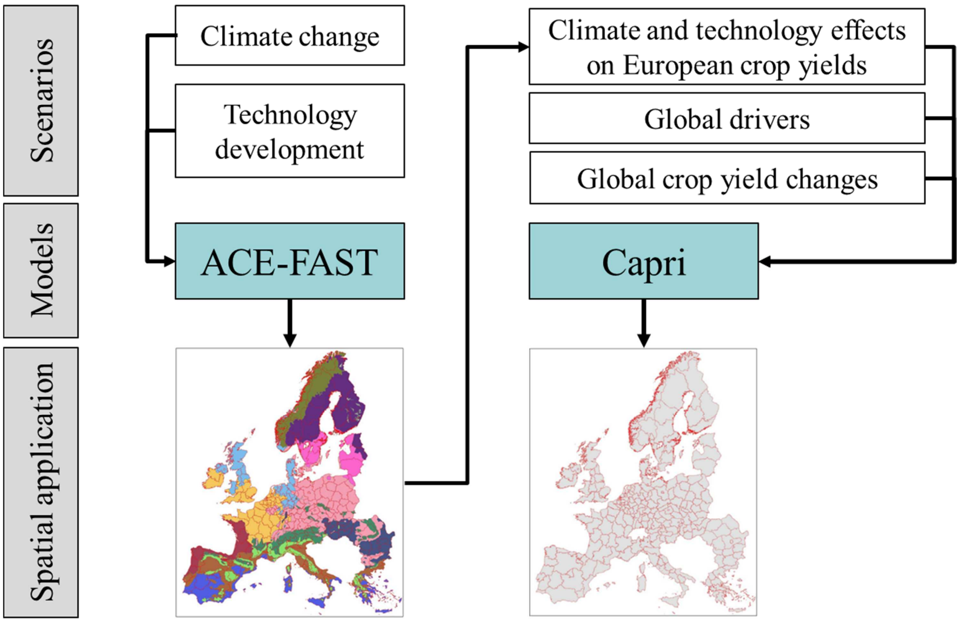

Figure 2. Overview of the scenario approach for the two models used in this study. The two maps indicate climate zones (as the simulation unit for ACE-FAST) and Nuts 2 regions (simulation unit for CAPRI). See text for further explanation.

2.2.2. Climate change scenarios

The climate changes scenarios considered projections to 2100 assuming alternative emissions pathways from 15 different general circulation models (GCM)s, archived as part of the third Coupled Model Intercomparison Project (CMIP3) at the Intergovernmental panel on Climate Change (IPCC) Data Distribution Centre (DDC) (DDC IPCC, 2010). The following seven GCM-based scenarios were selected to provide a wide range of changes in temperature and precipitation by the mid-21st century:

- **SRES A1B 15-model ensemble mean** – this provides a central estimate of changes with respect to all variables provided.
- **Pattern-scaled SRES B2 15-model ensemble mean** –: all changes of the A1B ensemble mean are reduced by a factor 0.90, more explanation see below.
- **BCCR_BCM2_0/SRES B1** – *less warming* consistent across all European regions and seasons
- **MIROC3.2(hires)/SRES A1B** – *more warming* consistent across all European regions and seasons
- **CCCMA-CGCM3.1/SRES A2** – wet in NEU[2]
- **MIROC3.2(hires)/SRES B1** – wet in MED
- **GISS_MODEL_E_H/SRES A1B** – dry in MED and NEU

Changes in temperature simulated by individual GCMs are fairly consistent across Europe; two simulations could therefore be identified that span a large part of the range of temperature changes simulated by all GCMs investigated for all seasons and all parts in Europe. As precipitation changes vary across Europe and between seasons considerably, no single

[2] This scenario could be replaced by MIROC3_2_hires/B1, to reduce to the total number of climate scenarios, although precipitation changes of the latter are a bit less consistently on the wet side.

simulation provides consistent dry or wet conditions throughout the year and in all parts of Europe. Two GCMs each have been selected for northern and southern European conditions separately to represent dry and wet conditions, although also this selection does not cover the full range of precipitation changes in all seasons.
One GCM, IAP-FGOALS1.0g, was showing exceptionally cold conditions in high latitudes in the control run and was therefore not considered a possible candidate. All simulations were checked to provide plausible values for all variables needed to construct the scenarios.

Changes in annual temperature and precipitation for northern (NEU) and southern Europe (MED) are shown in Figure 3. Changes in northern Europe in the other variables required to calculate scenarios are shown in Figure 4.

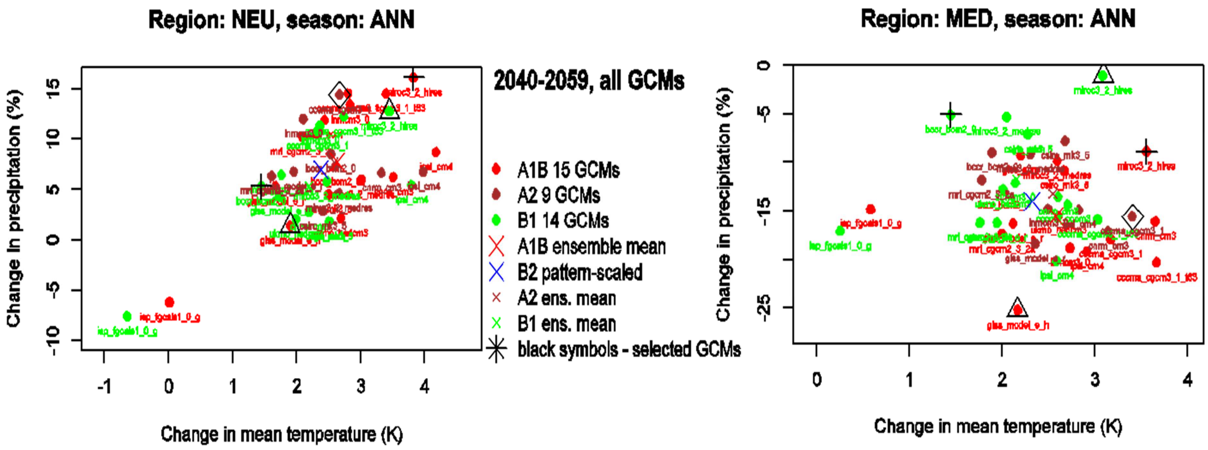

Figure 3. Changes in temperature and precipitation for Northern (left; land grid cells in 10W-40E, 48N-75N) and Southern Europe (right; 10W-40E, 30N-48N) by 2040-2059 wrt. 1980-1999 as simulated with a large number of GCMs; seven simulation results are selected for AgriAdapt shown with larger symbols.

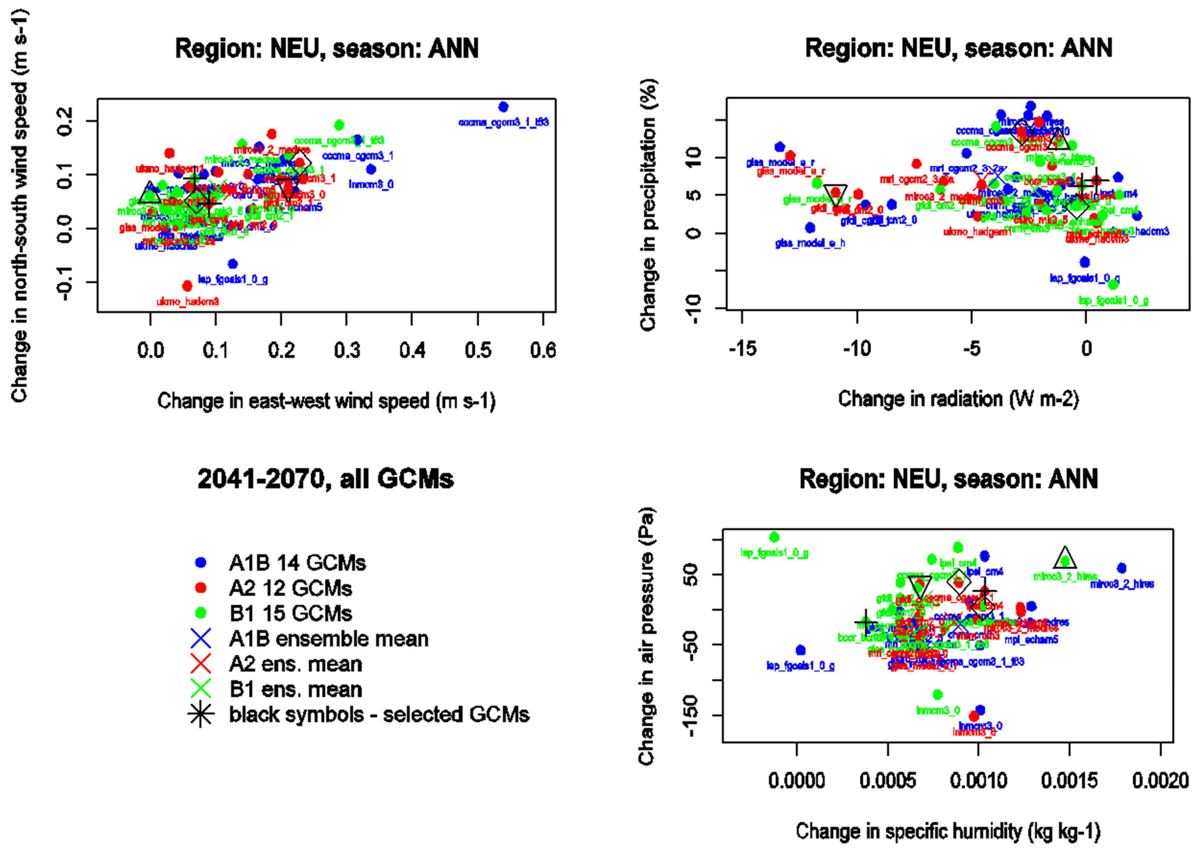

Figure 4. Changes in sea-level air pressure and specific humidity (top right), precipitation and radiation (bottom left) and meridional and zonal wind speeds (bottom right) for Northern Europe by 2041-2070 wrt. 1971-2000 as simulated with a large number of GCMs; seven simulation results are selected for AgriAdapt shown with larger symbols.

2.2.2.1. Calculating simulated monthly changes from GCMs

Simulated monthly changes between baseline and future period from GCM output are added to the observed time series. Simulated changes are calculated between the scenario and baseline periods for precipitation (pr), mean 2-m temperature (tas) and surface-downwelling shortwave flux in the air (rsds).

Near-surface (usually, 10 meters) wind speed is treated by climate models in its zonal and meridional directions separately; the real wind speed of a single time step can be calculated from these [sqrt(uas^2 +vas^2)]. However, for most climate models, only monthly mean values are available from the data archive which causes a potential underestimation of the real wind speed.[3] We assume that this can be neglected since only changes in wind speed are used for constructing climate scenarios. A comparison of wind speed changes estimated with a GCM simulation from the ENSEMBLE project indicated that this might over- or underestimate changes in wind speed by up 30%.

Vapour pressure is not directly simulated by GCMs. Mitchell et al. (2004) in the ATEAM scenarios suggested two alternative approaches to estimate vapour pressure based on GCM output using either sea level air pressure (psl) and specific humidity (huss) (ATEAM method 1) or using relative humidity (hur), mean and minimum temperatures (tas, tasmin)

[3] Consider a hypothetical situation in one month where all wind is blowing directly in north-south direction with a wind speed of 1 m/s during half of the days and in east-west direction during the other half of the days. As the wind speed on each day is 1 m/s, the average wind speed for the month is also 1 m/s. The average wind speed in north-south and east-west directions is 0.5 m/s. On the other hand, calculating the wind speed from monthly mean directional wind speeds results in sqrt(0.5^2 +0.5^2)=0.71 m/s.

(ATEAM method 2). As minimum temperatures were available for only very few GCMs from the CMIP3 archive, we employed ATEAM method 1. A comparison of both methods for a single GCM showed that method 2 gives larger changes in vapour pressure in northern Europe by up to 20%.

Table 1. Variables used to construct AgriAdapt climate scenarios.

Observed variable (daily)	GCM variable (monthly mean) from which to derive deltas	Method of calculation
PR [mm]	Precipitaton flux (pr) [kg m-2 s-1]	Relative change
TX [°C]	Mean surface temperature (tas) [K]	Absolute change
TN [°C]	Mean surface temperature (tas) [K]	Absolute change
GR [MJ m-2 d-1]	Surface downwelling shortwave flux in air (rsds) [W m-2]	Relative change
WS [m s-1]	Zonal (uas) and meridional wind speed (vas) [m s-1]	Absolute change in WS determined as WS = sqrt(uas*uas+vas*vas)
VP [hPa]	Air pressure at sea level (psl) [Pa] Specific humidity (huss) [kg kg-1] Relative humidity at the highest pressure level (hur) tasmin	Absolute change in VP calculated as (ATEAM method 1): VP = huss * psl / 0.62 Alternatively (ATEAM method 2): VP=hur*e_s/100 e_s=f(tas,TN)

2.2.2.2. Calculation of A1B ensemble mean and pattern-scaling to B2

Simulated changes of GCM have been calculated for all variables and all regions for 15 GCMs with SRES A1B forcing and averaged over the 15 models. For relative changes, the ensemble averages have been first calculated for the absolute values of the baseline and scenario periods before calculating the relative change.

Simulations for the SRES B2 scenario have not been conducted with the GCMs analysed in this work or were not available from the CMIP3 archive. In order to provide climate projections for the B2 scenarios, we applied a simple version of the pattern-scaling method (Ruosteenoja *et al.*, 2003). Pattern-scaling factors were obtained from the simple climate model MAGICC that emulates GCM-response to different forcing scenarios and provides estimates of global mean temperature[4]. The spatial pattern of changes for climate variables, also other variables then temperature, from one GCM simulation is then linearly scaled to different forcing scenarios. Global mean temperature changes were emulated both for the A1B and B2 scenarios for 13 of the 15 GCMs that we used for the A1B-ensemble

[4] Pattern-scaling factors from MAGICC were provided by S. Raper and M. Meinshausen.

mean. The reason for these two GCMs not being emulated with MAGICC was that climate sensitivity, one of the parameters needed to emulate GCM response, was not available. However, the two GCMs show temperature and precipitation changes in Europe relatively close to the 15-GCM-ensemble mean and it is therefore reasonable to assume that their exclusion from calculating an ensemble-mean scaling factor has a minor effect.
The ratio between the global mean temperature change of the B2- and A1B- 13-GCM-ensemble mean for the year 2050 is 2.0593/2.2819=0.9024. The pattern-scaled B2 15-GCM-ensemble was calculated by multiplying the monthly changes for all variables with this factor.

2.2.2.3. Applying changes to daily observed time series

Simulated monthly GCM-changes were interpolated to daily changes using cubic splines. This gives a smooth curve of daily values that avoids "steps" from one month to the next. Daily changes were repeated 25 times and applied to the observed time series 1982-2006. Absolute changes were added, relative changes were multiplied.
The baseline period, 1980-1999, does not exactly match the observed period, 1982-2006, for practical reasons to be consistent with the IPCC AR4 and as pattern-scaling factors to scale to the SRES B2 scenario were only available for the period 1980-99.
To represent statistics of the scenario period 2040-59, such as the mean or variability of yield, we recommend using the first 20 years of the climate scenarios only. This could be compared to statistics of the baseline period using also the first 20 years, 1982-2001, to compare periods of the same length.

Simulation results of the nth year of the reference period are directly comparable to the nth year of the scenario period. For direct comparison of scenario results with simulation results of any year between 2000 and 2006, the last 5 years of the scenario data can be used.

2.2.3. Changes in CO_2 concentration

The CO_2 present and future atmospheric concentrations for the climate change scenarios A1B, B1, A2 and B2 were taken from the SRES report (IPCC, 2001) (**Table** 2).

Table 2. CO2 atmospheric concentration (in ppm) for the scenarios A1B, A2, B1 and B2 in the period from 1980 to 2060 (IPCC, 2001).

Year	Scenario			
	A1B	A2	B1	B2
1980	337	337	337	337
1990	353	353	353	353
2000	369	369	369	369
2010	391	390	388	388
2020	420	417	412	408
2030	454	451	437	429
2040	491	490	463	453
2050	532	532	488	478
2060	572	580	509	504

2.2.4. Technology development

The importance of considering technology development in climate change impact assessments studies has been stressed by several authors (Ewert *et al.*, 2005; Challinor *et al.,* 2009; Semenov & Halford, 2009; Rötter *et al.*, 2011). Here we use the approach described in (Ewert *et al*., 2005) to estimate yield changes due to improved varieties and crop management. In this approach, historic yield trends are used as a basis to extrapolate yields into the future. The extrapolated trends are, however, modified depending on scenario specific assumptions about breeding progress to increase potential yields and crop management to reduce the yield gap (Ewert *et al*., 2005). In this study we used the same technology parameters to correct the historic yield trends as described in (Ewert *et al*., 2005). Importantly, historic trends were calculated for the period 1983-2006 for each NUTS2 region and disaggregated to the climate zone. Thus, all climate zones in one NUTS2 region use the same historic yield trend. Calculated scenario-specific yield changes due to technology development were then used to correct simulated yields under climate change and increased [CO_2].

2.2.5. Changes of global (macro) economic drivers and crop yields for CAPRI

There are three types of scenario parameters applied to one CAPRI scenario in this study. The first type of parameters defines the regional crop yields derived from the ACE simulation. Thereby we could not simply take over the absolute numbers from ACE, because of differences in yield definition (dry weight versus harvested weight) and some database differences although both models work with EUROSTAT data. As already said before, crop yields for a certain scenario (like B2) where defined by using the CAPRI Baseline yields multiplying them by the relation of APES yields in B2 over those from B1.1. We furthermore had to make certain assumption to extrapolate the APES results form 5 crops to the complete CAPRI activity list and all CAPRI NUTS2 regions. Thereby the following procedure was applied.

1. Transformation of ACE yields of change factor compared to B1.1
2. Statistical checks to detect and eliminate outliers in simulation results.
3. Aggregation of simulated crops to groups (harvest in summer, harvest in autumn, all crops, see table 3)
4. Mapping of all CAPRI crops to a probably comparable combination of specific crops or groups. see table 4.
5. Aggregation to average at MS level.
6. Derive missing MS data from neighboring countries.
7. Derive missing Nuts2 data from MS average

Table 3. Definition of activity groups based on crops simulated by ACE. As not all crops considered in CAPTRI were simulated with ACE. Thus results of crops simulated with ACE had to be extrapolated to all crops used in CAPRI. As part of this aggregation crops were grouped in summer and autumn harvested crops.

Group of activities	Related crops
Havest in summer	Wheat and Barley
Harvest in autumn	Potaoe and Maiz
All crops	Wheat, Barley, Maize and Potatoe

Table 4. Mapping of specific CAPRI activities to available crops and groups. This table was used to extrapolate results for crops simulated with ACE to the crops used in CAPRI. For instance, oats was not simulated by ACE. Thus, the yield response of oats was derived from the simulated response of wheat and the simulated response of all simulated ACE crops (with considered with a weight of 50%) to changes in climate, CO_2 and technology development.

Crop	Harvest Summer	Harvest Autumn	All Crops	Barley	Wheat	Maize	Potatoe	No Change
SWHE	50%				50%			
DWHE	50%			50%				
RYEM	50%			50%				
BARL	50%			50%				
OATS	50%				50%			
MAIZ		50%				50%		
OCER	50%			50%				
RAPE	50%			50%				
SUNF	50%			50%				
SOYA	50%			50%				
OOIL	50%			50%				
OIND		50%	50%					
NURS								100%
FLOW								100%
OCRO								100%
NECR			100%					
MAIF		50%				50%		
ROOF		50%				50%		
OFAR		50%	50%					
GRAE		50%	50%					
GRAI		50%	50%					
PARI	50%		50%					
OLIV			50%					50%
PULS	50%			50%				
POTA		50%					50%	
SUGB		50%				50%		
TEXT			50%					50%
TOBA			50%					50%
TOMA								100%
OVEG			50%					50%
APPL			50%					50%
OFRU			50%					50%
CITR			50%					50%
TAGR			50%					50%
TABO			50%					50%
TWIN			50%					50%
FALL								100%
ISET								100%
GSET		50%	50%					
TSET			50%					50%
VSET								100%

The second type of parameters allude to the macroeconomic environment namely population and GDP growth. They were taken from older IMPACT simulation made available by Rene Verburg. Again, those where mapped to the CAPRI definition of world regions and defined relative to the B1.1 scenario. Since the data was available at country level no extrapolation procedure was needed. However, preliminary simulation experiments revealed that effects of changes in GDP dominate model results. Hence, simulations were done for reduced changes in GDP (0%, 25% and 50% of IMPACT simulation)

Finally, also assumptions of climate effects on yields in the rest of the world had to be reflected. Unfortunately, there are not yet many studies assessing the effects of climate change on crop yields on a global level. We found a background note in the world development report by Müller et al. (2010). There at least average crop yield effects for some of the IPPC scenarios (A1 and B1) are published. We use this scarce information to receive some response on results for the rest of the world to climate change, which appears more appropriate than assuming climate change only happening in the EU. The procedure to define supply shift in the rest of the world was the following:

1. Transformation of yields development over time in change factors compared to B1 scenario.
2. Calculation of average effects of various models and model assumptions to derive pattern of world wide yield effects.
3. Apply constant shifts (+0.1, +0.05, -0.05, -0.1) to get different level of overall yield effects
4. Mapping CAPRI aggregate to (most overlapping) simulated regions, see Table 5.
5. Mapping ACE simulation to comparable world effects (based on EU results), see table 6.
6. Apply Change factor to all tradable crops outputs.
7. Apply reduced change factor to animal products to capture effects of non-tradable feed stocks (Beef: 80%, Milk: 50%, Pork and Poultry: 20%). Effects of tradable feed stocks are captured by cross price effects.

The Common Agricultural Policy in the EU in the base year is implemented as declared in the so called 2003 CAP reform. Future simulations consider the changes made in the 2009 Health check. In the A1 scenarios a trade liberalization according to the 2009 Falconer proposal is implemented. A summary of the CAPRI scenario settings are given in Table 7.

Table 5. Mapping CAPRI aggregates to simulated world regions

CAPRI Aggregate	Simulated world Region	Comment
Rest of Europe	Europe	Capri Region is part of simulated region
Russia, Belarus and Ukraine	Former Soviet Union	
USA	North America	
Canada	North America	
Mexico	Latin America	
Venezuela	Latin America	
Argentina	Latin America	
Brazil	Latin America	
Chile	Latin America	
Uruguay	Latin America	
Paraguay	Latin America	
Bolivia	Latin America	
Rest of South America	Latin America	
India	South Asia	
China	Centrally-Planned Asia	
Japan	Pacific OECD	
Australia and New Zealand	Pacific OECD	
Morocco	Middle East/North Africa	
Tunesia	Middle East/North Africa	
Algeria	Middle East/North Africa	
Egypt	Middle East/North Africa	
Israel	Middle East/North Africa	
LDC	Sub-Saharan Africa	Definition not matching, but significant overlap
ACP non LDC	Sub-Saharan Africa	
Rest of world	Middle East/North Africa	

Table 6. Mapping ACE scenarios to worldwide simulation

Change Factor World	A1b_sens+10	A1b_sens+5	**A1b**	A1b_sens-5	A1b_sens-10	
Europe	1.09	1.04	**0.99**	0.94	0.89	
North America	1.03	0.98	**0.93**	0.88	0.83	
Latin America	1.03	0.98	**0.93**	0.88	0.83	
Middle East/North Afri	1.08	1.03	**0.98**	0.93	0.88	
Sub-Saharan Africa	1.09	1.04	**0.99**	0.94	0.89	
Centrally-Planned Asia	1.14	1.09	**1.04**	0.99	0.94	
South Asia	1.12	1.07	**1.02**	0.97	0.92	
Pacific OECD	1.07	1.02	**0.97**	0.92	0.87	
Change Factor APES at EU level	a1b_1		a1b_3		a1b_2	b2
Wheat	1.10		1.01		0.74	0.88
Barley	1.08		1.01		0.72	0.90
Maize	0.89		0.79		0.74	0.75
Potatoes	1.03		0.92		0.66	0.83
Sugarbeet	1.05		0.89		0.67	0.80

Table 7. Description of CAPRI scenarios

	Base year [2004]	B1 (Baseline) [2050]	B2 [2050]	A1_b1 [2050]	A1_b2 [2050]	A1_b3 [2050]
Exogenous assumptions	Observed data (average 2003 - 2005) taken from EuroStat, FAO, OECD etc.	Inflation rate of 1.9% per year				
		constant exchange rates				
		Projection of GDP	Derived from IMPACT scenarios (decreasing demand for agricultural	Derived from IMPACT scenarios (leading to increasing demand for agricultural products compared to B2)		
		Projection of population (growth)				
Commodity Prices	Observed prices (average 2003 - 2005)	Extrapolated from market outlooks (European Commisssion and IFPRI)	Simulation results			
Input Prices	Observed prices (average 2003 - 2005)	Extrapolated from market outlooks (constant in all simulations)				
Yield	Observed yields (average 2003 - 2005)	Trend projection combined with APES simulation (BCCR_BCM2_0/SRES B1 - less warming consistent across all European regions and seasons)	Apes siumlation (Pattern-scaled SRES B2 15-model ensemble mean)	Apes siumlation (SRES A1B 15-model ensemble mean)	Apes siumlation (MIROC3.2(hires)/SRES A1B - more warming consistent across all European regions and seasons)	Apes siumlation (GISS_MODEL_E_H/SRES A1B - dry in MED and NEU)
Set-aside and quota policies	With obligatory set-aside and quota (milk and sugar)	Abolishing obligatory set-aside, expiry of milk quota, continuation of sugar quota				
Premium scheme	2003 CAP reform (decoupled + partially coupled payment)	2009 Health Check (decoupled payment, increased modulation)				
WTO trade policy	Tariffs and TRQ as in 2004	Tariffs and TRQ as in 2004		Reduction of tariffs and expansion of TRQ (sensitive products) as proposed by Falconer (2010)		

3. Results

3.1. Calibration results for ACE-FAST

3.1.1. Effect of calibration method on simulations crop productivity

3.1.1.1. Baseline conditions

Simulations considering only phenology (i.e. method 1, section 2.5.2) resulted in large differences between simulated and observed yields for all crops as depicted exemplarily for winter wheat in Fig. 5a. In fact, no relationship between simulated and observed yields could be obtained. Considering region-specific correction factors for yield simulations (i.e. method 2, section 2.5.2) noticeably improved simulation results, but there was still considerable disagreement between observed and simulated yields (Fig. 5b). Finally, the simulations based on a more extended calibration of growth parameters (i.e. method 2, section 2.5.2) resulted in a substantial improvement with very good agreement between simulated yields and observations (Fig. 5c).

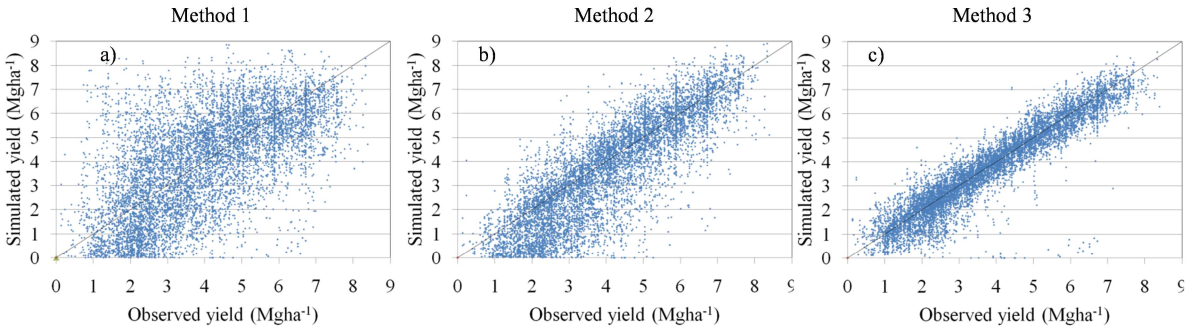

Figure 5. Comparison between observed and simulated yields from three calibration methods; (a) phenology only, (b) using a yield correction factor, and (c) an extended calibration of selected growth parameters of winter wheat for 533 climate zones in Europe in the period from 1983 to 2006. See text for explanation of calibration methods.

3.1.1.2. Climate change effects

Further analysis revealed that the simulated climate change effects depend on the calibration method used. For instance, the simulated yield difference between the climate change scenarios (here:15 GCM A1B) and the baseline was higher for the method in which a yield correction factor was used (method 2) as compared to the method in which only phenology was calibrated (method 1) (Fig. 6a). Diversion from the 1:1 line (Fig. 6b) indicates that simulated climate change effects were more pronounced when a yield correction factor was used. However, for simulated relative yield changes difference in climate change effects between the two calibration methods were small (Fig. 6b).

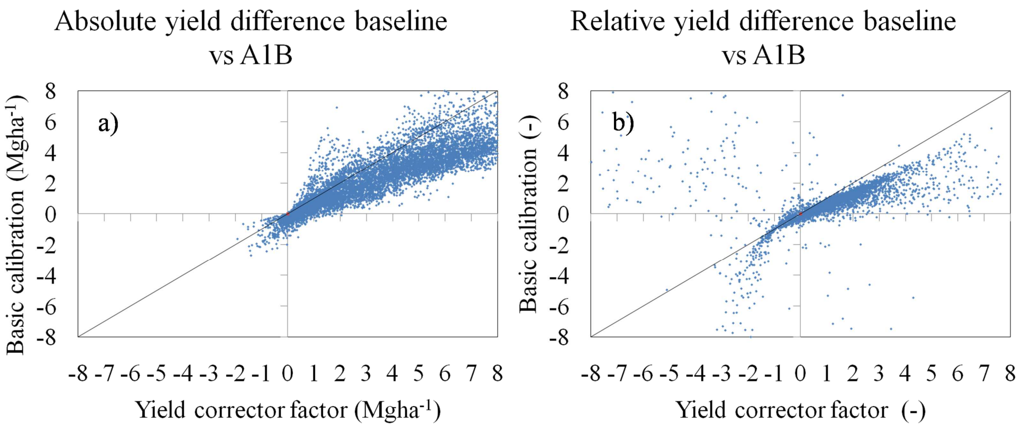

Figure 6. (a) absolute and (b) relative (related to baseline) yield differences between yield simulations of the baseline and the 15 GCM A1B climate scenario from calibration using the yield correction factors (calibration method 2) vs. calibration of phenology only (calibration method 1), for winter wheat in 533 climate zones in Europe over 23 years. See text for explanation of calibration methods.

Larger differences were found between calibration method 1 (phenology parameters only) and method 3 (phenology and growth parameters) for the simulated climate change effects on yield (Fig. 7a). Higher climate change effects were simulated with method 1 as compared to method 3 suggesting that with a more accurate calibration estimated climate change effects may be less pronounced. There was no such systematic deviation between the two methods when relative yield changes were compared, but some deviations were noticed (Fig. 7b).

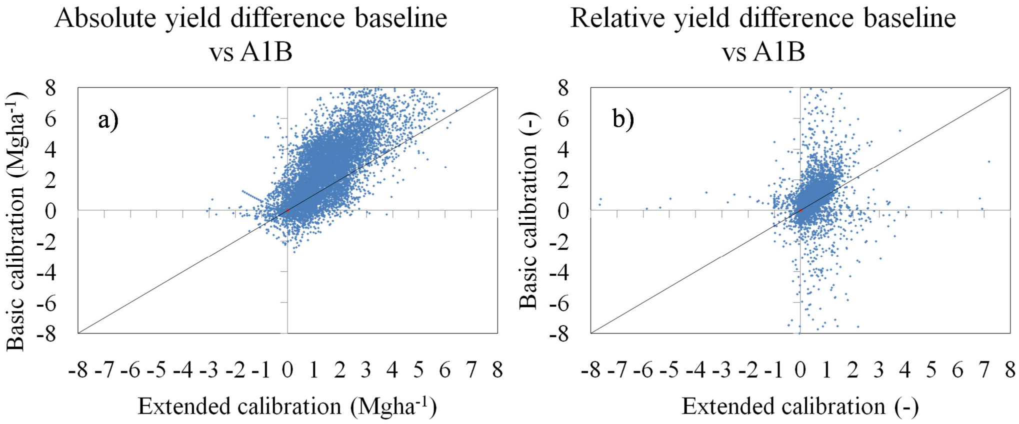

Figure 7. (a) absolute and (b) relative (related to baseline) yield differences between yield simulations of the baseline and the 15 GCM A1B climate scenario from extended calibration of growth parameters (calibration method 3) vs. calibration of phenology only (calibration method 1), for winter wheat in 533 climate zones in Europe over 23 years. See text for explanation of calibration methods.

The differences between calibration methods in simulating climate change effects were largest when method 3 (growth parameters) and method 2 (yield correction factor) were compared. Simulated climate change effects were considerably higher when the model was calibrated according to method 3 as compared to a calibration following method 2 (Fig. 8a). Again, no systematic deviation between the two methods was found when the relative effects of climate change were compared (Fig. 8b).

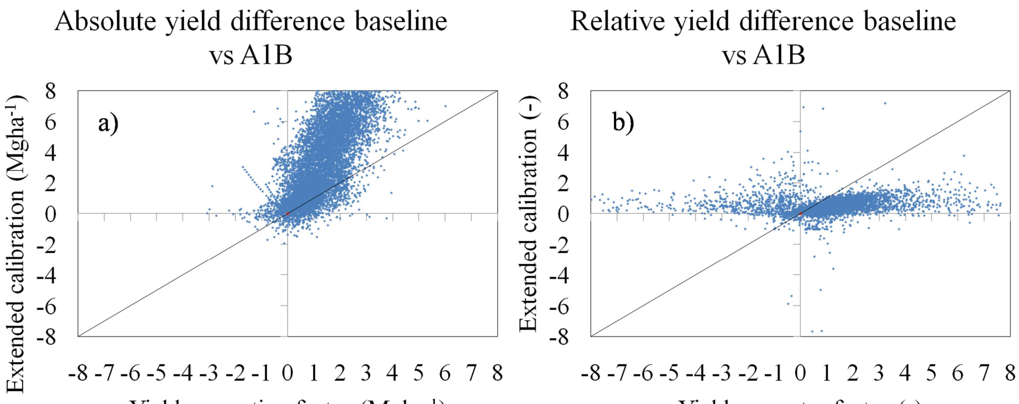

Figure 8. (a) absolute and (b) relative (related to baseline) yield differences between yield simulations of the baseline and the 15 GCM A1B climate scenario from calibration using a yield correction factor (calibration method 1) vs. extended calibration of growth parameters (calibration method 3) for winter wheat in 533 climate zones in Europe over 23 years. See text for explanation of calibration methods.

3.1.2. Spatial and temporal variability of calibration results

As evident from Fig. 5 model calibration considering growth parameters (method 3) provided the best agreement between observed and calibrated yields. Thus, further analysis was restricted to this calibration method.

A comparison of the simulated spatial pattern of wheat yields averaged over the 24 years period (1983-2006) with the observations over the same time period showed good agreement between simulated and observed data (Fig. 9). The model was capable of reproducing high productivity regions in Central and Western Europe (France, Belgium, The Netherlands and Germany) as well as the low productivity regions in the Mediterranean countries (Spain, Italy and Greece) (Fig. 9).

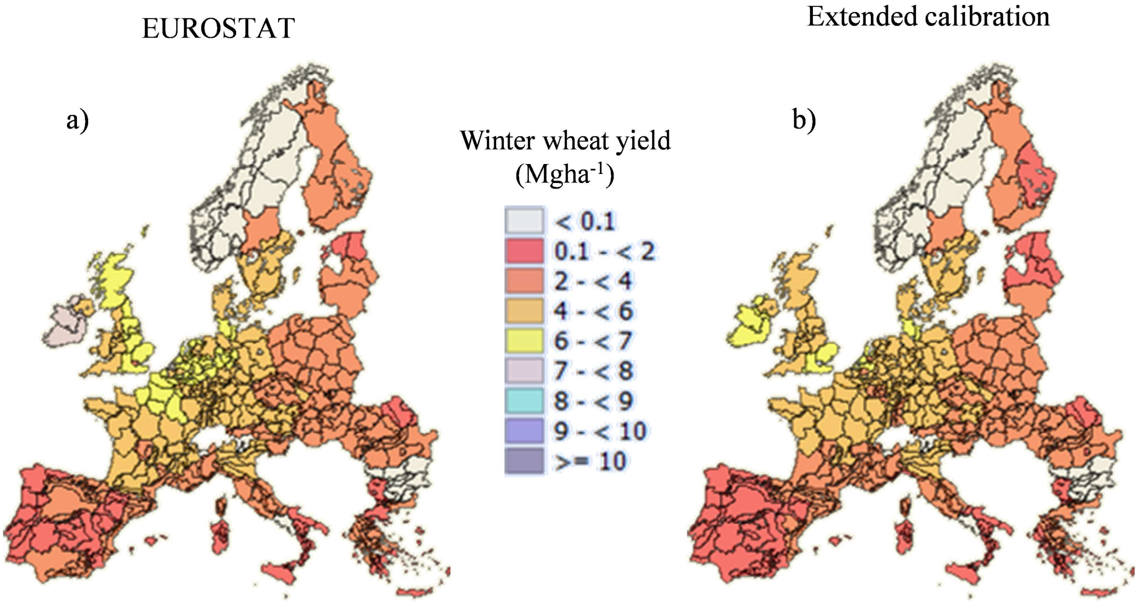

Figure 9. Spatial pattern of (a) observed and (b) simulated winter wheat yields (Mg ha^{-1}) based on extended calibration of selected growth parameters (calibration method 3) for winter wheat for 533 climate zones in Europe averaged over 23 years (1983 to 2006).

This good agreement between simulated and observed data is not surprising as spatial differences are considered in the calibration through region-specific parameters. However, more interesting was to analyse whether the model was also able to reproduce the temporal variability of yields within each regions and for the entire EU25 as no calibration was performed for individual years. The simulated yields agreed well with the observed temporal yield variability of individual regions (see Figs. 10a-c for selected regions). The agreement was always better when regions had observations for all or most years available (not shown). Thus, the more observations, the better the calibration results were for the temporal variability. Remarkably, at the aggregated level of EU25 the temporal variability of wheat yields was very well reproduced (Fig. 10d) with the calibrated model.

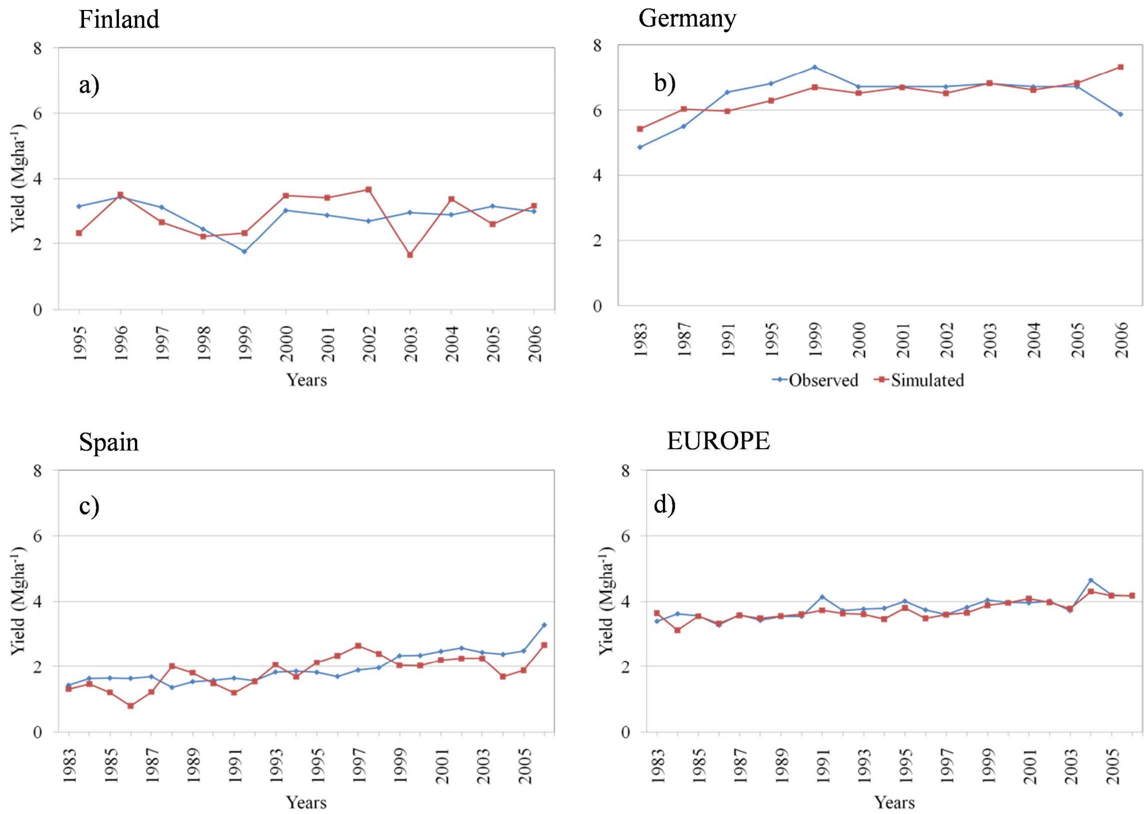

Figure 10. Temporal yield variability of observed (blue) and calibrated (red) winter wheat yields (Mg ha^{-1}) of three locations (a) South Finland, (b) Cologne region in Germany and (c) Galicia in Spain, and (d) on average over EU25 for the period from 1983 to 2006.

3.1.3. Calibrations for other crops

Calibration results for other crops based on method 3 (phenology and growth parameters) were fairly satisfactory but some differences were observed (Fig. 11). Yield simulations were in better agreement with observations for winter wheat and barley yields as compared to potato, maize and sugar beet yields, with the latter showing the largest differences. One reason for the larger differences between observed and simulated data for the spring crops as compared to the winter cereals could be the limited (or incorrect) availability of phenology data, particularly sowing dates. Discrepancies of some weeks between estimated and observed sowing date are more important and can have a large impact when simulating spring crops as compared to winter crops.

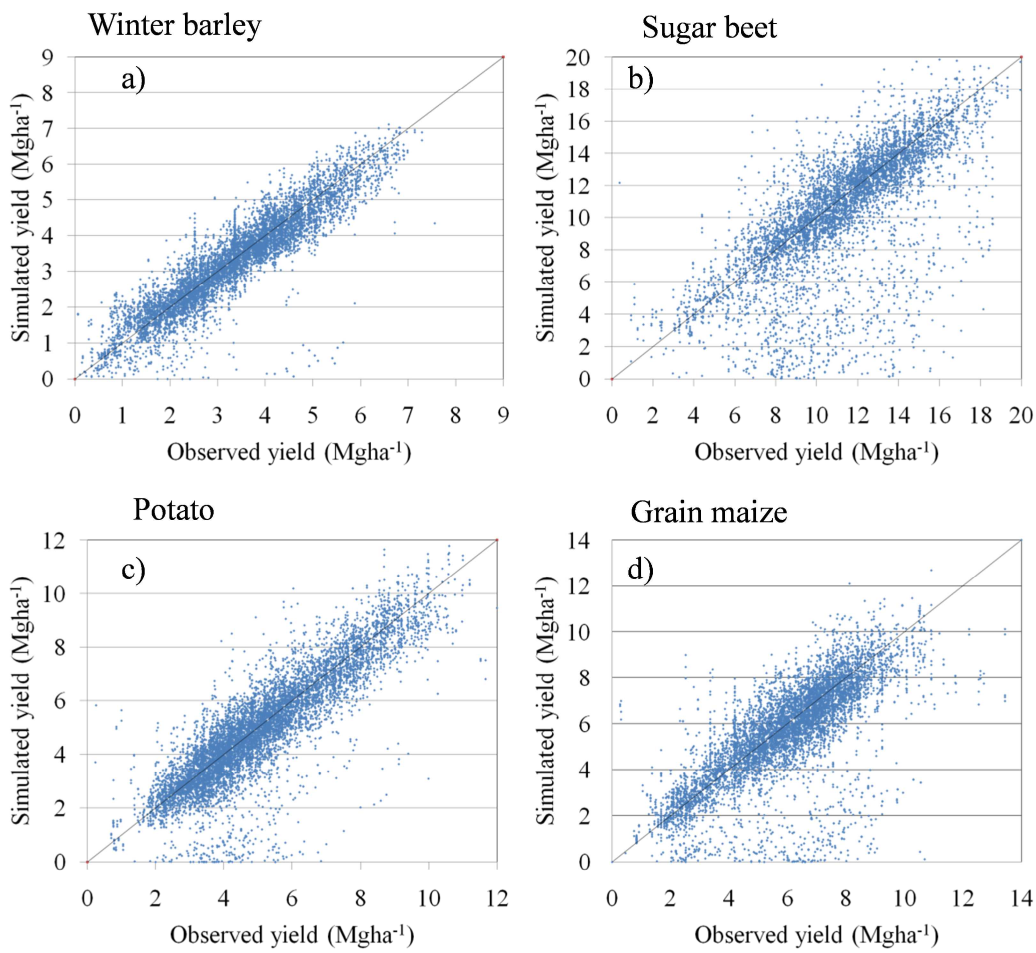

Figure 11. Comparison between observed and calibrated yields of four crops in Europe (EU25) considering 533 climate zones and 24 years (1983 to 2006). (a) winter barley, (b) sugar beet, (c) potato, (d) grain maize.

Simulated spatial (Fig. 12) and temporal (not shown) variability of yields in Europe for the selected crops are in acceptable agreement with observations. High productivity regions observed in Central and Western Europe (France, Netherlands, Belgium, Germany) for barley, potato and sugar beet are reproduced well by the model. For grain maize, the highest yields are typically recorded in southern regions (Spain, Italy, Greece) which the calibration method also captured. For some zones and crops e.g. winter barley for Finland, phenological parameters were missing and no model calibration and simulation was performed.

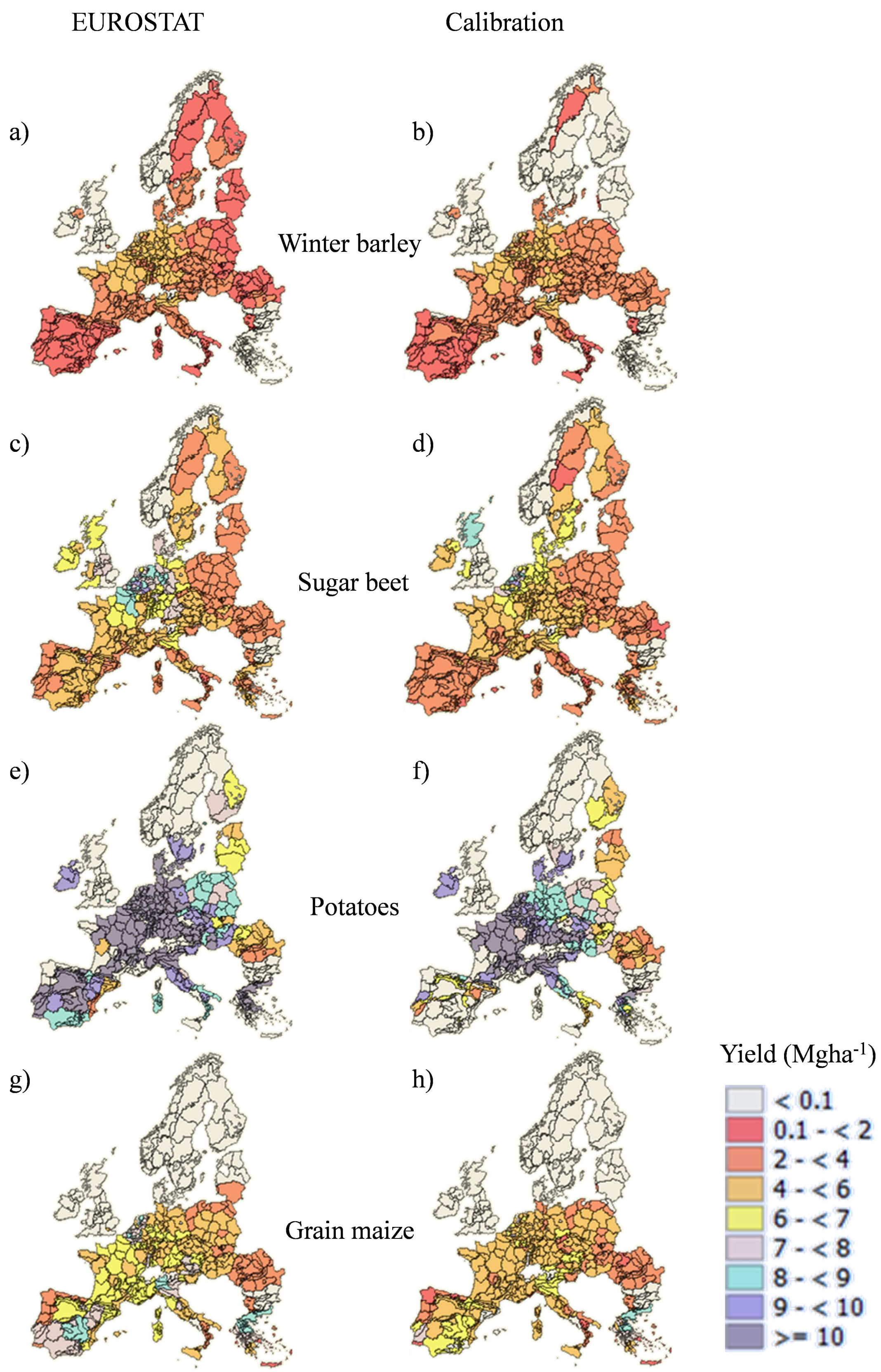

Figure 11. Spatial pattern of observed (a,c,e,g) and simulated (b,d,f,h) yields (Mg ha^{-1}) based on extended calibration of selected growth parameters (calibration method 3) for (a,b) winter barley, (c,d) potato, (e,f) sugar beet) and (g,h) maize in Europe averaged for the period 1983 to 2006.

3.2. Simulations of future crop yields in Europe

3.2.1. Impact of climate change

Climate change without considering increasing atmospheric [CO_2] and advances in technology, causes a yield decrease for all crops and scenarios compared to the baseline yields (Fig. 12a,d,g,j,m). The largest yield declines due to climate change were simulated with the GISS A1B scenario, a predominantly dry scenario. However, differences between crops were observed. Projected climate change impacts on yields were largest for maize, approximately -1.7 Mg ha^{-1} (Fig. 12m) and smallest for winter wheat, about -0.4 Mg ha^{-1} on average over EU25 (Fig. 12a). We also realized that simulated responses to climate change were less for winter crops as compared to spring crops. This may be due to the longer vegetative period typical for winter crops, which allows winter crops to recover better from extreme events such as drought spells in spring. Also, climate change induced changes in growing season length due to temperature increase will be relatively smaller in winter as compared in spring crops.

3.2.2. Combined impacts of climatic change and increased [CO_2]

Taking into account elevated [CO_2] when simulating climate change impacts increases simulated yields for all crops and scenarios but with some variation. Yield increases are highest for the winter crops and compensate for the negative yield effect due to climate change (Fig. 12b,e). In these crops projected future yields are higher than baseline yields for all scenarios. Also for the root crops, sugar beet and potatoes, the simulated yields are higher than the baseline yields in most scenarios; but for the scenario with the largest climate change impact, Giss A1B, the positive [CO_2] effect cannot compensate for the negative effect of climate change (Fig. 12h,k). For grain maize, as C4 plant, there is only an insignificant increase in yields due to [CO_2] since only an effect of [CO_2] on transpiration rate was considered but not in radiation use efficiency (Fig. 12n).

3.2.3. Combined impacts of climate change, increased [CO_2] and technology development

When both the effect of increased [CO_2] and technology development are taken into consideration together with the effect of climate change, simulated yield increases are considerable (Fig. 12c,f,i,l) but with some noticeable differences among the crops. While for winter cereals and the root crops, yield increases are higher than the baseline for all future scenarios, simulated grain maize yields remain below the baseline yields (Fig. 12o). Apparently, the simulated pronounced climate change effect on maize yield could not be compensated by increased [CO_2] and technology development. For the other crops, the highest yield increases are simulated for A1B scenario (Fig. 12c,f,i,l), in which [CO_2] abundance and temperature reach the highest values. Importantly, the consideration of technology development results also in larger differences of simulated yields among the scenarios.

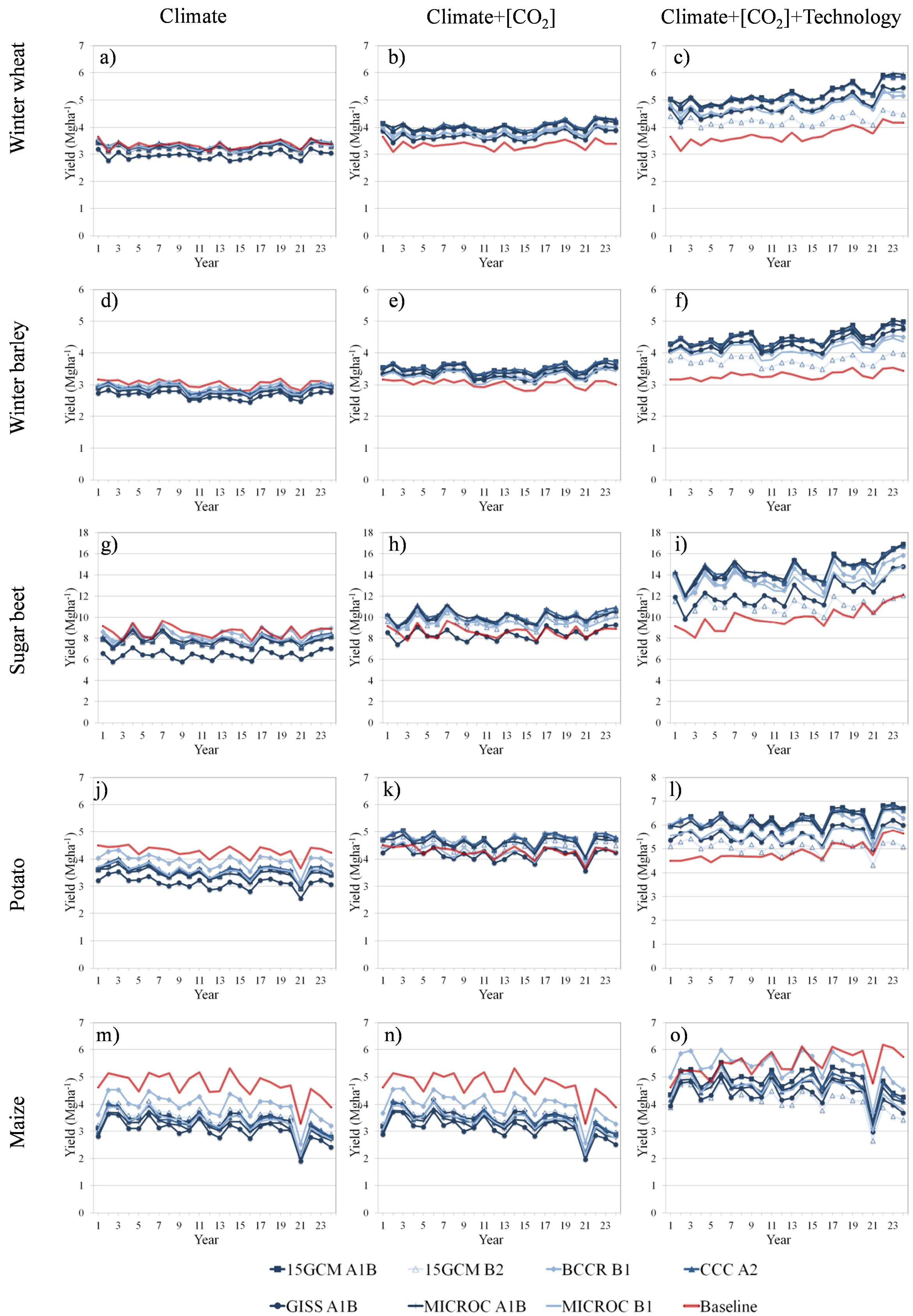

Figure 12. Simulated effects of (a,d,g,j,m) climate change, (b,e,h,k,n) climate change and increased [CO_2], and (c,f,i,l,o) climate change, increased [CO_2] and technological development on yields of five crops for 24 years in Europe (EU25) using four IPCC CC scenarios. Baseline and future scenarios. centred around 1990 and 2050 respectively. Crops considered are winter wheat (a,b,c), winter barley (d,e,f), sugar beet (g,h,i), potato (j,k,l) and maize (m,n,o).

An analysis of the spatial variability of simulated yields under combined changes in climate, [CO_2] and technology shows little differences among scenarios as can been seen from the comparison of yield simulation from A1B and B1, although some differences in the extent of yield changes in the individual regions can be noticed (Fig. 13). For the winter cereals yield increases of 30% and more compared to the baseline are simulated for most regions. There are small areas on the Iberian and Italic peninsulas were yield decreases are projected compared to the baseline, which however, do not exceed 10% (Fig. 13b,d). These declines are mainly due to the pronounced negative climate change effect which could not be compensated for by the positive [CO_2] and technology effect. The latter is relatively small due to the comparably small yield increases for these regions observed in the past. For potatoes and sugar beet yields increases are also simulated for most regions in Europe except for some areas in south Europe (Italy, Greece and Spain), and few regions in Poland and Finland, but the decreases do not surpass 10% in relation to baseline. For grain maize the spatial variability in yield changes ranges between -30% and more to 30% and more (Fig. 13i,j). Yield increases are highest in South-western Europe and yield declines are mainly projected for Eastern Europe.

Figure 13. Differences between simulated baseline yields and yields from two climate change scenarios (a,c,e,g,i) A1B and (b,d,f,h,j) B1 for 5 crops over 24 years in Europe (EU25). The baseline and future time series are centred around 1990 and 2050, respectively. Crops considered are winter wheat (a,b), winter barley (c,d), sugar beet (e,f), potato (g,h) and maize (i,j).

Finally, we compared the temporal variability of our future projections with the baseline and the observed yield variability. Results are shown for three selected crops representing the range of responses for all five crops (Fig. 14). The crop model ACE-FAST reproduces well the observed yield variability for all crops and most regions as was already described above. However, we realized some overestimations of the yield variability for potatoes and maize on the Iberian Peninsula. This may be due to an overestimation of the drought effect in the model. This overestimation can be expected for models applying the RUE concept instead of detailed photosynthesis routines (e.g. Rötter *et al.*, in press). However, yield variability was reproduced satisfactorily in most regions.
There were only small changes in yield variability for the projected future scenarios for most crops, accept for maize (Fig. 14g,h,i). The coefficients of variation (CV) of simulated grain maize decreased for the climate change scenarios as compared to the baseline on the Iberian Peninsula (Fig. 14g,h).On the other hand, an increase in yield variability of maize due to climate change was observed for some regions in east Europe, mainly Poland (Fig. 14g,h).

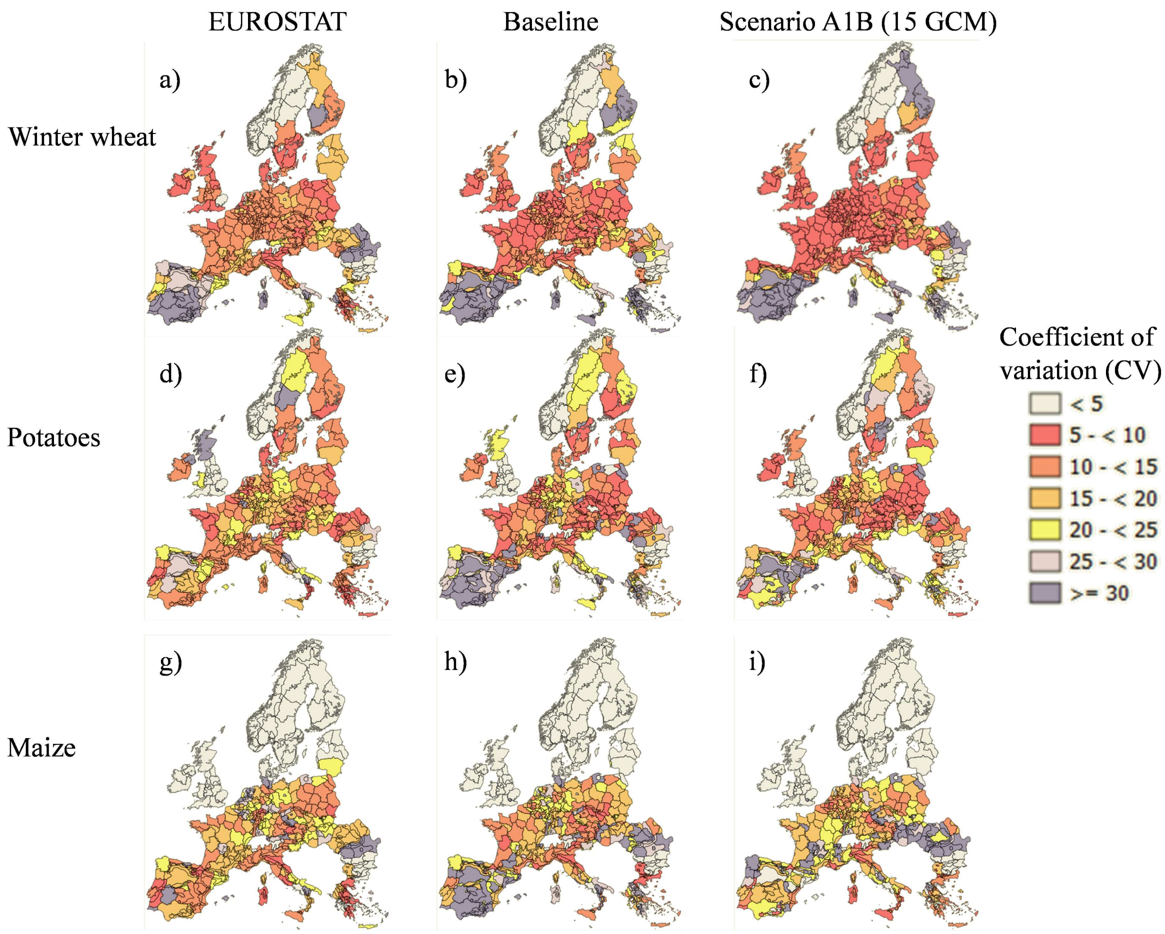

Figure 14. Coefficient of Variation over 24 years in Europe for (a,c,g) observed and simulated yields for (b,e,h) baseline and (c,f,i) A1B scenario. Crops shown are winter wheat (a,b,c), potato (d,e,f) and maize (g,h,i).

3.3. Price changes due to climate, CO_2 and technology

The simulated scenarios comprise shocks on the supply site (yield changes) as well on the demand site (population and GDP). Further world wide trade liberalization according to probable WTO rules (tiered tariff reduction, expansion of tariff rate quotas, and abolition of export subsidies) is assumed in some scenarios.

The simulated yield changes are:

- a1b_1 (SRES A1B 15-model ensemble mean)
- a1b_2 (MIROC3.2(hires)/SRES A1B - more warming consistent across all European regions and seasons)
- a1b_3 (GISS_MODEL_E_H/SRES A1B - dry in MED and NEU)
- b1 (BCCR_BCM2_0/SRES B1 - less warming consistent across all European regions and seasons)
- b2 (Pattern-scaled SRES B2 15-model ensemble mean)

In order to analyze effects of changing yields independent from demand shocks we carried out simulations combing a change in yields with:

- Constant GDP and population
- GDP and population changing as predicted by GTAP (different for A1 and B2 scenarios)
- 25% of the GDP and population change
- 50% of the GDP and population change

The A1 scenario assumes tiered tariff reduction, expansion of tariff rate quotas and abolition of export subsidies according to actually discussed WTO modalities of the Doha Development Round (WTO, 2008). In order to separate impacts all a1 scenarios are simulated with and without trade liberalization.
The b1 scenario comes closest to the CAPRI baseline projection for 2050. Hence this scenario is used for comparison.

Among many other variables, the CAPRI model output comprises market prices at global level which are typically used to analyze changes and plausibility of simulation results. National prices (so called producer prices) are derived from the market price. In the following section simulation results are discussed at European level. Subsequently the Dutch producer prices are presented.

3.3.1. Market Price effects in EU27

Figures 15 and 16 visualize the development of the European wheat price under various scenario settings. Compared to the baseline scenario b1 the price can increase by up to 200%, while price drop is at most -10%. Yield impacts (ignoring demand changes) cause price effects between -12% and +75%. The macro economic assumptions in all a1 scenarios strongly influence the price effects. In each a1 scenario the difference between no and full GDP shock is about 100%. Marco economic assumptions cause (slightly) more variation in the results than yield effects. It should be noted that the consumption patter is assumed to be unchanged. Different assumptions regarding the consumption of meat might also have significant effects on the results (not tested so far).

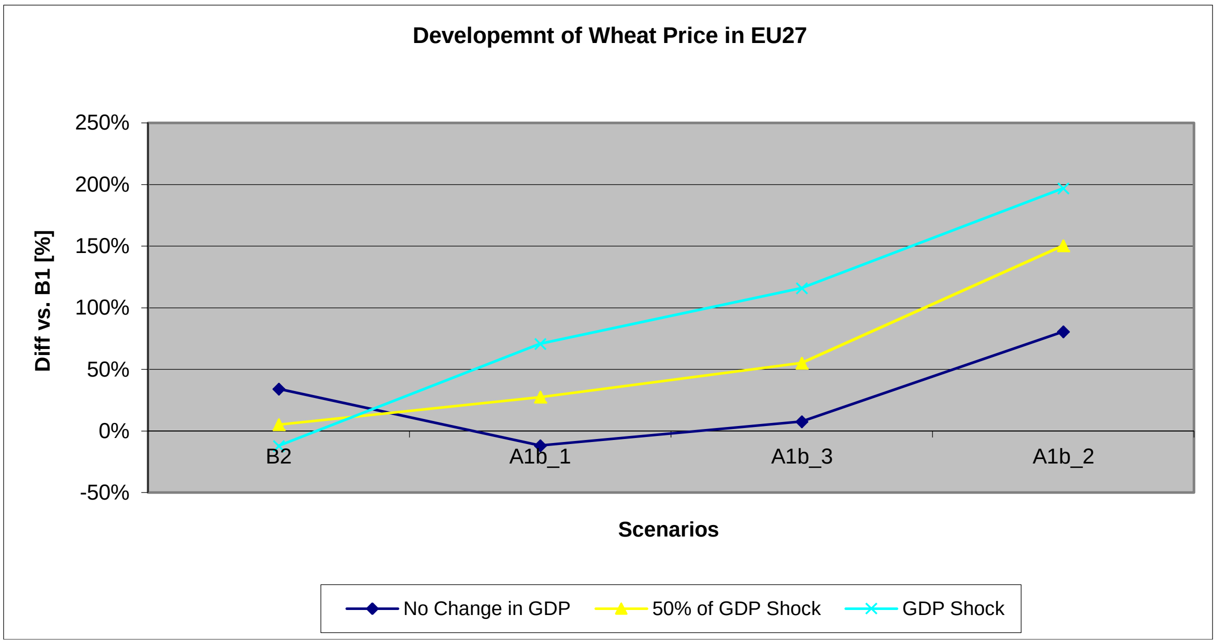

Figure 15. Development of wheat price in various scenarios.

Compared to the effects of yields and demand shocks, the influence of trade liberalization is rather small differing at most 10% from the comparable scenario without liberalization (see Fig. 16). There is a tendency that trade liberalization leads to increasing wheat prices. When agricultural prices go up, exports from the EU increase. Following EU farmers would profit from trade liberalization. It has to be noted that the trade liberalisation effects on prices for agriculturak goods is not the same across commodities. Those products that experience actually higher degree of border protection than wheat (like meat e.g.) are showing price decreases.

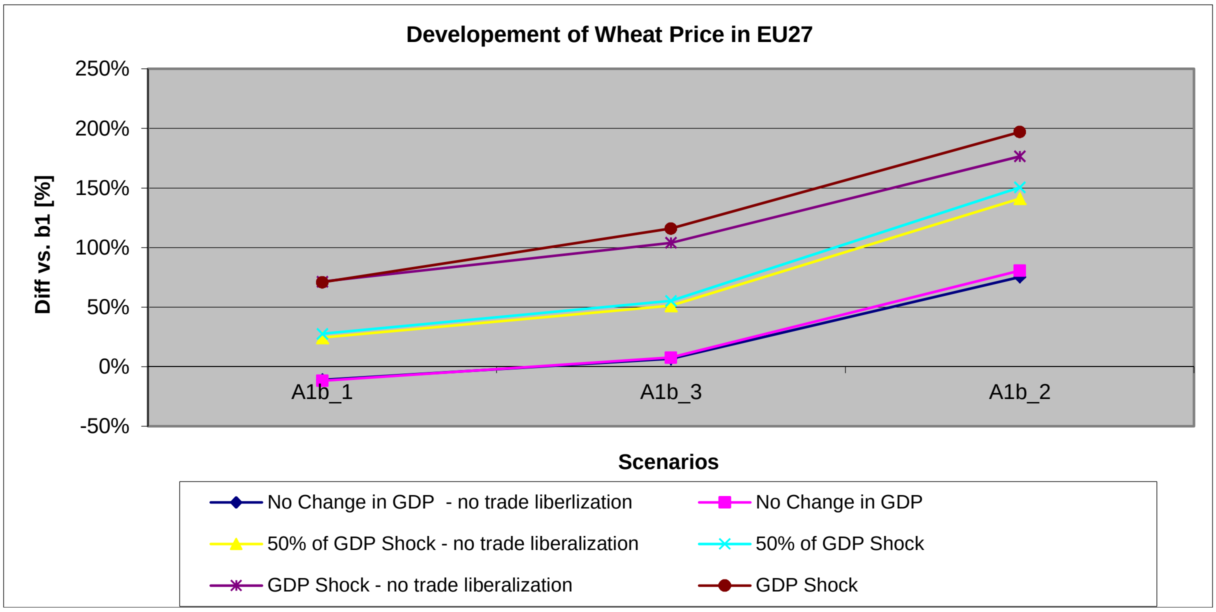

Figure 16. Effect of trade liberalization on wheat price in various scenarios. Scenarios range from no trade liberalization (left) to trade liberalization (right).

Results so far show that the development of yields subject to climate change as well as projections of the macro-economic environment can lead to fundamental changes in agricultural prices. Compared to other simulations (CAP reform, WTO scenarios, milk quota abolition) carried out so far with the CAPRI models the observed price changes are higher. However, the shocks implemented in the model are tremendous as well. Yields (and subsequently supply) of arable field crops decreases up to 25% in the a1b1_2 scenarios. Since demand elasticities for agricultural commodities are generally low the price effects can be significantly higher. Further wheat prices were rather volatile during recent years, whereas the maximum price was more than twice of the minimum price. All in all, the model results seem drastic but can be seen as plausible given the scenario assumptions.

Following results are presented in more detail. The b2 scenario simulates a decline in yields combined with decreasing demand due lower population and GDP compared to the b1 comparison scenario. These shocks potentially cancel each other out. If demand would be constant (b2 – no change in GDP) prices of arable field crops would increase in a range of 20% to 45% (see table 5). Due to increasing prices for feed stocks animal product would become more expensive either [14%, 32%]. When accounting for the decreasing demand projected for this scenario, prices mainly decrease compared to b1, i.e. the shock on the demand site overcompensates the yield reduction. Prices of arable field crops are rather stable [-12%, + 3%] while animal products become significantly cheaper [-41%, - 5%].

			Bas (B1)eline	b2 No Change in GDP	b2 25% of GDP Shock (B2)	b2 50% of GDP Shock (B2)	b2 GDP Shock (B2)
European Union 27	Wheat	[EUR/ton]	146.86	197	171.53	154.62	129.19
		[%diff. b1]		34%	17%	5%	-12%
European Union 27	Barley	[EUR/ton]	105.65	145.97	126.95	115.13	97.71
		[%diff. b1]		38%	20%	9%	-8%
European Union 27	Grain maize	[EUR/ton]	104.25	145.36	129.18	119.38	103.75
		[%diff. b1]		39%	24%	15%	0%
European Union 27	Other cereals	[EUR/ton]	123.92	176.28	148.71	132.54	110.4
		[%diff. b1]		42%	20%	7%	-11%
European Union 27	Rape seed	[EUR/ton]	369.74	466.15	437.84	419.66	383.62
		[%diff. b1]		26%	18%	14%	4%
European Union 27	Pulses	[EUR/ton]	168.35	244.88	213.99	194.81	158.07
		[%diff. b1]		45%	27%	16%	-6%
European Union 27	Potatoes	[EUR/ton]	105.5	129.09	121.18	118.77	109.12
		[%diff. b1]		22%	15%	13%	3%
European Union 27	Tomatoes	[EUR/ton]	255.81	268.54	254.42	248.53	236.2
		[%diff. b1]		5%	-1%	-3%	-8%
European Union 27	Other fruits	[EUR/ton]	513.06	626.22	540.43	514.41	389.47
		[%diff. b1]		22%	5%	0%	-24%
European Union 27	Beef	[EUR/ton]	2735.73	3613.3	2984.53	2661.7	1874.32
		[%diff. b1]		32%	9%	-3%	-31%
European Union 27	Pork meat	[EUR/ton]	1309.62	1733.16	1566.59	1488.28	1248.19
		[%diff. b1]		32%	20%	14%	-5%
European Union 27	Poultry meat	[EUR/ton]	3467.58	4373.74	3846.06	3536	2574.76
		[%diff. b1]		26%	11%	2%	-26%
European Union 27	Rape seed cake	[EUR/ton]	138.2	182.65	164.22	153.36	133.98
		[%diff. b1]		32%	19%	11%	-3%
European Union 27	Soya Cake	[EUR/ton]	366.47	478.09	427.65	404.28	343.1
		[%diff. b1]		30%	17%	10%	-6%
European Union 27	Sugar	[EUR/ton]	401.83	379.03	352	331.84	246.25
		[%diff. b1]		-6%	-12%	-17%	-39%
European Union 27	Butter	[EUR/ton]	1941.75	2077.58	1718.52	1617.78	1143.19
		[%diff. b1]		7%	-11%	-17%	-41%
European Union 27	Skimmed milk powder	[EUR/ton]	1310.52	1499.6	1343.02	1281.03	1053.76
		[%diff. b1]		14%	2%	-2%	-20%

Table 8. Price effects on crops of the B2 climate change scenario vs. the baseline for different assumptions about changes in GDP.

All a1 scenarios assume a significant increase in demand for human consumption paired with different yield expectations. In a1b_1 yields are assumed to increase slightly compared to b1. Ignoring demand shocks prices would decrease (moderately) about 10% (see table 9). When changes in GDP and population are considered prices almost double for some products. Prices of arable field crops increase about 75% [20%, 93%]. The price increase for animal products is even more significant [39%, 154%] since consumer demand increase strongly.

			B1	A1b_1 No Change in GDP	A1b_1 25% of GDP Shock (A1)	A1b_1 50% of GDP Shock (A1)	A1b_1 GDP Shock (A1)
European Union 27	Wheat	[EUR/ton]	146,86	130,83	154,49	182,71	251,67
		[%diff. b1]		-11%	5%	24%	71%
European Union 27	Barley	[EUR/ton]	105,65	94,45	112,25	132,75	185,24
		[%diff. b1]		-11%	6%	26%	75%
European Union 27	Grain maize	[EUR/ton]	104,25	99,76	114,49	131,58	175,02
		[%diff. b1]		-4%	10%	26%	68%
European Union 27	Other cereals	[EUR/ton]	123,92	109,56	132,9	159,06	220,91
		[%diff. b1]		-12%	7%	28%	78%
European Union 27	Rape seed	[EUR/ton]	369,74	327,17	371,15	419,48	535,17
		[%diff. b1]		-12%	0%	13%	45%
European Union 27	Pulses	[EUR/ton]	168,35	145,99	181,94	222,69	325,2
		[%diff. b1]		-13%	8%	32%	93%
European Union 27	Potatoes	[EUR/ton]	105,5	99,63	105,79	111,95	126,08
		[%diff. b1]		-6%	0%	6%	20%
European Union 27	Tomatoes	[EUR/ton]	255,81	248,77	265,33	280,26	321,31
		[%diff. b1]		-3%	4%	10%	26%
European Union 27	Other fruits	[EUR/ton]	513,06	476,15	531,87	590,51	712,52
		[%diff. b1]		-7%	4%	15%	39%
European Union 27	Beef	[EUR/ton]	2735,73	2406,32	2977,38	3757,13	5618,26
		[%diff. b1]		-12%	9%	37%	105%
European Union 27	Pork meat	[EUR/ton]	1309,62	1130,42	1645,33	2192,51	3322,61
		[%diff. b1]		-14%	26%	67%	154%
European Union 27	Poultry meat	[EUR/ton]	3467,58	3107,27	3894,49	4689,98	6330,35
		[%diff. b1]		-10%	12%	35%	83%
European Union 27	Rape seed cake	[EUR/ton]	138,2	122,94	150,71	181,47	268,86
		[%diff. b1]		-11%	9%	31%	95%
European Union 27	Soya Cake	[EUR/ton]	366,47	330,82	398,92	473,68	683,24
		[%diff. b1]		-10%	9%	29%	86%
European Union 27	Sugar	[EUR/ton]	401,83	398,02	414,9	418,81	481,5
		[%diff. b1]		-1%	3%	4%	20%
European Union 27	Butter	[EUR/ton]	1941,75	1899,14	2117,56	2314,38	2701,9
		[%diff. b1]		-2%	9%	19%	39%
European Union 27	Skimmed milk powder	[EUR/ton]	1310,52	1256,69	1385,94	1544,75	1933,37
		[%diff. b1]		-4%	6%	18%	48%

Table 9. Price effects on crops of the A1B_1 climate change scenario vs. the baseline for different assumptions about changes in GDP.

Since scenario a1b_2 assumes yields to decrease considerably while demand increases extreme results can be expected. Even when ignoring demand shocks prices would almost double [35%, 86%] (see table 10). When demand shocks are considered prices “explode”. E.g. Wheat prices would go up from 146€/ton to 406€/ton. This price increase of 177% seems high, but prices of almost 300€/ton were observed in 2007 when word wide cereal stocks shrunk rapidly. Hence results are plausible given the extreme scenario assumptions.

			B1	A1b_2 No Change in GDP	A1b_2 25% of GDP Shock (A1)	A1b_2 50% of GDP Shock (A1)	A1b_2 GDP Shock (A1)
European Union 27	Wheat	[EUR/ton]	146,86	257,44	362,31	354,11	406,08
		[%diff. b1]		75%	147%	141%	177%
European Union 27	Barley	[EUR/ton]	105,65	196,56	312,31	274,05	324,26
		[%diff. b1]		86%	196%	159%	207%
European Union 27	Grain maize	[EUR/ton]	104,25	180,68	238,63	244,11	286,24
		[%diff. b1]		73%	129%	134%	175%
European Union 27	Other cereals	[EUR/ton]	123,92	242,86	340,36	342,16	493,46
		[%diff. b1]		96%	175%	176%	298%
European Union 27	Rape seed	[EUR/ton]	369,74	597,69	807,62	777,22	872,09
		[%diff. b1]		62%	118%	110%	136%
European Union 27	Pulses	[EUR/ton]	168,35	330,23	670,87	504,58	1025,07
		[%diff. b1]		96%	298%	200%	509%
European Union 27	Potatoes	[EUR/ton]	105,5	163,78	184,95	187,27	219,86
		[%diff. b1]		55%	75%	78%	108%
European Union 27	Tomatoes	[EUR/ton]	255,81	283,92	331,12	335,95	418,14
		[%diff. b1]		11%	29%	31%	63%
European Union 27	Other fruits	[EUR/ton]	513,06	770,9	1188,85	946	1120,93
		[%diff. b1]		50%	132%	84%	118%
European Union 27	Beef	[EUR/ton]	2735,73	4629,23	6794,66	6977,44	9099,88
		[%diff. b1]		69%	148%	155%	233%
European Union 27	Pork meat	[EUR/ton]	1309,62	2175,22	3196,56	3522,39	4814,6
		[%diff. b1]		66%	144%	169%	268%
European Union 27	Poultry meat	[EUR/ton]	3467,58	5190,91	7036,34	7140,15	8909
		[%diff. b1]		50%	103%	106%	157%
European Union 27	Rape seed cake	[EUR/ton]	138,2	233,46	312,12	325,6	412,28
		[%diff. b1]		69%	126%	136%	198%
European Union 27	Soya Cake	[EUR/ton]	366,47	605,77	777,44	849,04	1117,44
		[%diff. b1]		65%	112%	132%	205%
European Union 27	Sugar	[EUR/ton]	401,83	422,26	572,23	564,4	752,79
		[%diff. b1]		5%	42%	40%	87%
European Union 27	Butter	[EUR/ton]	1941,75	2231,22	2499,78	2699,2	3264,71
		[%diff. b1]		15%	29%	39%	68%
European Union 27	Skimmed milk powder	[EUR/ton]	1310,52	1765,07	2056,68	2281,13	2543,37
		[%diff. b1]		35%	57%	74%	94%

Table 10. Price effects on crops of the A1B_2 climate change scenario vs. the baseline for different assumptions about changes in GDP.

In a1b_3 yields are assumed to decrease slightly compared to b1. Ignoring demand shocks prices would increase (moderately) about 10% (see table 11). When changes in GDP and population are considered prices of arable field crops almost double [54%, 116%]. The price increase for animal products is even more significant [45%, 187%] since consumer demand and production cost (feed stocks) are rising.

			Baseline (B1)	A1b_3 No Change in GDP	A1b_3 25% of GDP Shock (A1)	A1b_3 50% of GDP Shock (A1)	A1b_3 GDP Shock (A1)
European Union 27	Wheat	[EUR/ton]	146,86	156,94	187,51	222,13	299,67
		[%diff. b1]		7%	28%	51%	104%
European Union 27	Barley	[EUR/ton]	105,65	114,24	137,83	164,62	224,65
		[%diff. b1]		8%	30%	56%	113%
European Union 27	Grain maize	[EUR/ton]	104,25	123,59	144,55	168,71	225,49
		[%diff. b1]		19%	39%	62%	116%
European Union 27	Other cereals	[EUR/ton]	123,92	137,91	168,12	200,76	271,97
		[%diff. b1]		11%	36%	62%	119%
European Union 27	Rape seed	[EUR/ton]	369,74	377,21	434,08	489,54	570,51
		[%diff. b1]		2%	17%	32%	54%
European Union 27	Pulses	[EUR/ton]	168,35	186,79	231,4	281,97	370,9
		[%diff. b1]		11%	37%	67%	120%
European Union 27	Potatoes	[EUR/ton]	105,5	114,97	122,21	129,81	146,53
		[%diff. b1]		9%	16%	23%	39%
European Union 27	Tomatoes	[EUR/ton]	255,81	259,5	275,18	293,18	342,02
		[%diff. b1]		1%	8%	15%	34%
European Union 27	Other fruits	[EUR/ton]	513,06	549,59	614,47	680,17	816,23
		[%diff. b1]		7%	20%	33%	59%
European Union 27	Beef	[EUR/ton]	2735,73	2904,11	3699,07	4654,58	6628
		[%diff. b1]		6%	35%	70%	142%
European Union 27	Pork meat	[EUR/ton]	1309,62	1399,95	1980,69	2574,69	3756,05
		[%diff. b1]		7%	51%	97%	187%
European Union 27	Poultry meat	[EUR/ton]	3467,58	3696,48	4553,34	5425,36	7094,9
		[%diff. b1]		7%	31%	56%	105%
European Union 27	Rape seed cake	[EUR/ton]	138,2	149,42	182,54	219,33	285,27
		[%diff. b1]		8%	32%	59%	106%
European Union 27	Soya Cake	[EUR/ton]	366,47	396,17	479,83	579,05	742,81
		[%diff. b1]		8%	31%	58%	103%
European Union 27	Sugar	[EUR/ton]	401,83	357,36	385,94	417,95	532,96
		[%diff. b1]		-11%	-4%	4%	33%
European Union 27	Butter	[EUR/ton]	1941,75	1976,45	2202,85	2408,72	2810,86
		[%diff. b1]		2%	13%	24%	45%
European Union 27	Skimmed milk powder	[EUR/ton]	1310,52	1357,78	1524,12	1716,81	2131,07
		[%diff. b1]		4%	16%	31%	63%

Table 11. Price effects on crops of the A1B_3 climate change scenario vs. the baseline for different assumptions about changes in GDP.

3.3.2. Producer Price effects in Netherlands

The following tables show the producer price effects calculated for the Netherlands. The tendencies of price changes are similar to those describes before.

			Base year	b1 (baseline)	A1b_1 No Change in GDP	A1b_1 25% of GDP Shock (A1)	A1b_1 50% of GDP Shock (A1)	A1b_1 GDP Shock (A1)
Netherlands	Soft Wheat	[EUR/ton]	103,42	140,67	124,22	na	176,71	235,03
		[%diff. b1]			-12%	na	26%	67%
Netherlands	Barley	[EUR/ton]	85,9	89,33	78,55	na	114,22	155,48
		[%diff. b1]			-12%	na	28%	74%
Netherlands	Grain maize	[EUR/ton]	122	111,73	103,78	na	144,62	196,48
		[%diff. b1]			-7%	na	29%	76%
Netherlands	Other cereals	[EUR/ton]	101,11	106,75	91,58	na	133,81	179,87
		[%diff. b1]			-14%	na	25%	68%
Netherlands	Rape seed	[EUR/ton]	166,49	285,97	251,98	na	325,4	410,45
		[%diff. b1]			-12%	na	14%	44%
Netherlands	Pulses	[EUR/ton]	1524,78	1343,18	1155,64	na	1747,9	2426,67
		[%diff. b1]			-14%	na	30%	81%
Netherlands	Potatoes	[EUR/ton]	117,49	110,58	103,56	na	114,51	126,88
		[%diff. b1]			-6%	na	4%	15%
Netherlands	Sugar Beet	[EUR/ton]	42,76	32,58	23,66	na	22,83	27,14
		[%diff. b1]			-27%	na	-30%	-17%
Netherlands	Tomatoes	[EUR/ton]	776,57	616,8	592,47	na	641,59	711,31
		[%diff. b1]			-4%	na	4%	15%
Netherlands	Other Vegetables	[EUR/ton]	381,24	302,84	278,08	na	313,32	349,78
		[%diff. b1]			-8%	na	3%	15%
Netherlands	Other fruits	[EUR/ton]	1257,47	1029,42	689,82	na	928,08	1156,39
		[%diff. b1]			-33%	na	-10%	12%
Netherlands	Beef	[EUR/ton]	3305,85	3198,24	2311,59	na	4267,15	4955,51
		[%diff. b1]			-28%	na	33%	55%
Netherlands	Pork meat	[EUR/ton]	1321,93	1333,07	1143,39	na	2283,21	3541,49
		[%diff. b1]			-14%	na	71%	166%
Netherlands	Poultry meat	[EUR/ton]	911,47	1337,25	1204,13	na	1858,48	2581,88
		[%diff. b1]			-10%	na	39%	93%
Netherlands	Cow and buffalo milk	[EUR/ton]	324,68	211,88	178,28	na	231,61	284,37
		[%diff. b1]			-16%	na	9%	34%

Table 12. Producer Prices in the Netherlands – for the A1B_1 climate change scenario vs. the baseline for different assumptions about changes in GDP.

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			Base year	b1 (baseline)	A1b_2 No Change in GDP	A1b_2 25% of GDP Shock (A1)	A1b_2 50% of GDP Shock (A1)	A1b_2 GDP Shock (A1)
Netherlands	Soft Wheat	[EUR/ton]	103,42	140,67	248,4	na	341,66	542,24
		[%diff. b1]			77%	na	143%	285%
Netherlands	Barley	[EUR/ton]	85,9	89,33	169,08	na	236,27	384,9
		[%diff. b1]			89%	na	164%	331%
Netherlands	Grain maize	[EUR/ton]	122	111,73	190,43	na	265,28	461,35
		[%diff. b1]			70%	na	137%	313%
Netherlands	Other cereals	[EUR/ton]	101,11	106,75	193,41	na	295,95	455,58
		[%diff. b1]			81%	na	177%	327%
Netherlands	Rape seed	[EUR/ton]	166,49	285,97	460,16	na	561,47	592,11
		[%diff. b1]			61%	na	96%	107%
Netherlands	Pulses	[EUR/ton]	1524,78	1343,18	2540,52	na	3490,34	4337,61
		[%diff. b1]			89%	na	160%	223%
Netherlands	Potatoes	[EUR/ton]	117,49	110,58	163,25	na	184,65	263,19
		[%diff. b1]			48%	na	67%	138%
Netherlands	Sugar Beet	[EUR/ton]	42,76	32,58	30,47	na	39,42	61,7
		[%diff. b1]			-6%	na	21%	89%
Netherlands	Tomatoes	[EUR/ton]	776,57	616,8	663,81	na	759,99	843,05
		[%diff. b1]			8%	na	23%	37%
Netherlands	Other Vegetables	[EUR/ton]	381,24	302,84	420,65	na	464,02	527,9
		[%diff. b1]			39%	na	53%	74%
Netherlands	Other fruits	[EUR/ton]	1257,47	1029,42	1214,77	na	1558,89	1986,06
		[%diff. b1]			18%	na	51%	93%
Netherlands	Beef	[EUR/ton]	3305,85	3198,24	5323,44	na	8043,58	11374,28
		[%diff. b1]			66%	na	152%	256%
Netherlands	Pork meat	[EUR/ton]	1321,93	1333,07	2264,21	na	3715,76	5339,93
		[%diff. b1]			70%	na	179%	301%
Netherlands	Poultry meat	[EUR/ton]	911,47	1337,25	2024,75	na	2864,96	3696,04
		[%diff. b1]			51%	na	114%	176%
Netherlands	Cow and buffalo milk	[EUR/ton]	324,68	211,88	248,28	na	323,12	378,49
		[%diff. b1]			17%	na	53%	79%

Table 13. Producer Prices in the Netherlands – for the A1B_2 climate change scenario vs. the baseline for different assumptions about changes in GDP.

			Base year	b1 (baseline)	A1b_3 No Change in GDP	A1b_3 25% of GDP Shock (A1)	A1b_3 50% of GDP Shock (A1)	A1b_3 GDP Shock (A1)
Netherlands	Soft Wheat	[EUR/ton]	103,42	140,67	149,48	na	213,44	301,25
		[%diff. b1]			6%	na	52%	114%
Netherlands	Barley	[EUR/ton]	85,9	89,33	96,64	na	141,07	202,3
		[%diff. b1]			8%	na	58%	126%
Netherlands	Grain maize	[EUR/ton]	122	111,73	128,05	na	181,29	261,44
		[%diff. b1]			15%	na	62%	134%
Netherlands	Other cereals	[EUR/ton]	101,11	106,75	115,68	na	164,24	227,29
		[%diff. b1]			8%	na	54%	113%
Netherlands	Rape seed	[EUR/ton]	166,49	285,97	292,27	na	375,97	493,59
		[%diff. b1]			2%	na	31%	73%
Netherlands	Pulses	[EUR/ton]	1524,78	1343,18	1433,06	na	2178,16	2954,36
		[%diff. b1]			7%	na	62%	120%
Netherlands	Potatoes	[EUR/ton]	117,49	110,58	115,85	na	128,99	144,16
		[%diff. b1]			5%	na	17%	30%
Netherlands	Sugar Beet	[EUR/ton]	42,76	32,58	23,55	na	25,1	30,92
		[%diff. b1]			-28%	na	-23%	-5%
Netherlands	Tomatoes	[EUR/ton]	776,57	616,8	609,65	na	687,8	692,92
		[%diff. b1]			-1%	na	12%	12%
Netherlands	Other Vegetabl	[EUR/ton]	381,24	302,84	314,5	na	351,34	392,14
		[%diff. b1]			4%	na	16%	29%
Netherlands	Other fruits	[EUR/ton]	1257,47	1029,42	815,67	na	1077,01	1344,16
		[%diff. b1]			-21%	na	5%	31%
Netherlands	Beef	[EUR/ton]	3305,85	3198,24	2970,96	na	5293,69	8288,62
		[%diff. b1]			-7%	na	66%	159%
Netherlands	Pork meat	[EUR/ton]	1321,93	1333,07	1444,69	na	2682,06	4001,06
		[%diff. b1]			8%	na	101%	200%
Netherlands	Poultry meat	[EUR/ton]	911,47	1337,25	1440,84	na	2144,71	2909,96
		[%diff. b1]			8%	na	60%	118%
Netherlands	Cow and buffal	[EUR/ton]	324,68	211,88	191,88	na	249,4	312,44
		[%diff. b1]			-9%	na	18%	47%

Table 14. Producer Prices in the Netherlands – for the A1B_3 climate change scenario vs. the baseline for different assumptions about changes in GDP.

			Base year	b1 (baseline)	b2 No Change in GDP	b2 25% of GDP Shock (B2)	b2 50% of GDP Shock (B2)	b2 GDP Shock (B2)
Netherlands	Soft Wheat	[EUR/ton]	103,42	140,67	186,12	163,03	147,84	124,79
		[%diff. b1]			32%	16%	5%	-11%
Netherlands	Barley	[EUR/ton]	85,9	89,33	122,33	107	97,17	82,71
		[%diff. b1]			37%	20%	9%	-7%
Netherlands	Grain maize	[EUR/ton]	122	111,73	153,83	135,75	124,78	108,17
		[%diff. b1]			38%	21%	12%	-3%
Netherlands	Other cereals	[EUR/ton]	101,11	106,75	145,05	119,1	104,64	83,92
		[%diff. b1]			36%	12%	-2%	-21%
Netherlands	Rape seed	[EUR/ton]	166,49	285,97	358,94	337,07	322,69	295,47
		[%diff. b1]			26%	18%	13%	3%
Netherlands	Pulses	[EUR/ton]	1524,78	1343,18	1908,04	1677,32	1532,62	1259,41
		[%diff. b1]			42%	25%	14%	-6%
Netherlands	Potatoes	[EUR/ton]	117,49	110,58	133,9	126,85	125,13	115,7
		[%diff. b1]			21%	15%	13%	5%
Netherlands	Sugar Beet	[EUR/ton]	42,76	32,58	31,7	31,5	29,88	22,83
		[%diff. b1]			-3%	-3%	-8%	-30%
Netherlands	Tomatoes	[EUR/ton]	776,57	616,8	641,3	610,27	598,06	574,73
		[%diff. b1]			4%	-1%	-3%	-7%
Netherlands	Other Vegetables	[EUR/ton]	381,24	302,84	358,61	313,03	312,83	265,43
		[%diff. b1]			18%	3%	3%	-12%
Netherlands	Other fruits	[EUR/ton]	1257,47	1029,42	1243,02	1068,69	1019,28	766,39
		[%diff. b1]			21%	4%	-1%	-26%
Netherlands	Beef	[EUR/ton]	3305,85	3198,24	4203,83	3487,48	3126,06	2221,37
		[%diff. b1]			31%	9%	-2%	-31%
Netherlands	Pork meat	[EUR/ton]	1321,93	1333,07	1773,44	1602,43	1517,72	1272,28
		[%diff. b1]			33%	20%	14%	-5%
Netherlands	Poultry meat	[EUR/ton]	911,47	1337,25	1688,92	1491,55	1365,81	995,35
		[%diff. b1]			26%	12%	2%	-26%
Netherlands	Cow and buffalo milk	[EUR/ton]	324,68	211,88	236,48	204,58	191,41	144,68
		[%diff. b1]			12%	-3%	-10%	-32%

Table 15. Producer Prices in the Netherlands – for the B2 climate change scenario vs. the baseline for different assumptions about changes in GDP.

Difficulties might arise from using the sugar beet prices reported in the tables. The CAPRI model mimics the current administrative regulations of the sugar market. Actually the EU applies a quota system with a fixed in quota price. Quantities within this quota receive lower prices. The reported prices are weighted averages of in quota and out of quota price, i.e. changing aggregation weights influence the price. E.g. when world market prices increase the out of quota price might increase as well. Hence farmers might tend to produce more sugar beet. Following the out of quota price gets a higher weight in aggregation what might reduce the average price for sugar beet (and is hence counterintuitive to increasing production). It is questionable if the common market organization for sugar will be in place in 2050, but a full liberalisation of the sugar market (no quotas, free trade) is impossible to simulate within actual design of the CAPRI model. We suggest deriving sugar beet prices from sugar prices of major exporting regions. (See table 16). In several scenarios the sugar price is above the actual (administrative) European price of 404€/ton.

			Baseline	A1b_1 No Change in GDP	A1b_1 25% of GDP Shock (A1)	A1b_1 50% of GDP Shock (A1)	A1b_1 GDP Shock (A1)
Mercosur countries	Sugar	[EUR/ton]	231,47	192,38	279,06	366,66	**552,6**
		[%diff. b1]		-17%	21%	58%	**139%**
ACP countries	Sugar	[EUR/ton]	238,07	200,52	272,58	348,78	**514,08**
		[%diff. b1]		-16%	14%	47%	**116%**
			Baseline	A1b_2 No Change in GDP	A1b_2 25% of GDP Shock (A1)	A1b_2 50% of GDP Shock (A1)	A1b_2 GDP Shock (A1)
Mercosur countries	Sugar	[EUR/ton]	231,47	**469,15**	**607,22**	**713,33**	**961,7**
		[%diff. b1]		**103%**	**162%**	**208%**	**315%**
ACP countries	Sugar	[EUR/ton]	238,07	**427,07**	**550,66**	**658,74**	**901,19**
		[%diff. b1]		**79%**	**131%**	**177%**	**279%**
			Baseline	A1b_3 No Change in GDP	A1b_3 25% of GDP Shock (A1)	A1b_3 50% of GDP Shock (A1)	A1b_3 GDP Shock (A1)
Mercosur countries	Sugar	[EUR/ton]	231,47	255,11	353,8	**454,51**	**657,89**
		[%diff. b1]		10%	53%	**96%**	**184%**
ACP countries	Sugar	[EUR/ton]	238,07	253,25	341,9	**425,9**	**630,72**
		[%diff. b1]		6%	44%	**79%**	**165%**
			Baseline	b2 No Change in GDP	b2 25% of GDP Shock (B2)	b2 50% of GDP Shock (B2)	b2 GDP Shock (B2)
Mercosur countries	Sugar	[EUR/ton]	231,47	340,09	268,55	205,29	92,1
		[%diff. b1]		47%	16%	-11%	-60%
ACP countries	Sugar	[EUR/ton]	238,07	328,68	258,21	189,65	76,33
		[%diff. b1]		38%	8%	-20%	-68%

Table 16. Development of sugar price in major exporting regions.

4. Discussion

4.1. Impacts of climate change, [CO_2] increase and technology development

Simulated climate change impacts ranged from moderately to severely negative, to moderately positive effects on yields, depending on whether merely climatic factors were taken into account, or climate change was analysed in combination with increasing atmospheric [CO_2] and advances in technology were considered. An important finding of this modelling study is that considering regional differences of model parameters related to crop growth in addition to crop phenology can considerably improve yield simulations at continental scale (EU25).

Our results also suggest that for EU25 climate change without considering increasing atmospheric [CO_2] and advances in technology resulted in negative effects on crop yields in the range of 11.7% and 34.4% depending on the crop and region. Negative climate change effects are less pronounced for winter cereals (barley and wheat) as compared to tuber crops (potatoes and sugar beet) or other spring crops (maize). One possible explanation, still subject of further investigation, is the longer vegetative period for winter crops which may allow the winter crops to better recover from extreme events such as drought spells in spring. Also, changes in growing season length due to temperature increase will be relatively smaller in winter as compared to spring crops.

GISS A1B is the scenario with the strongest negative influence on yields even when taking the [CO_2] fertilization effect (Rötter and van de Geijn, 1999; Tubiello *et al*., 2007) into account. This is most likely related to the dry conditions projected in this scenario which were more pronounced in this than in other scenarios. The overall range in simulated yield changes among scenarios is large with clear differences among crops. Again, the range was less pronounced for winter-sown as compared to spring-sown crops. For the latter, on average for EU25 the differences among scenarios were larger than the climate change effect within one scenario or the simulated temporal yield variability.

The changes that we simulated are more pronounced than those projected by Ewert *et al*, (2005) who applied a statistical approach to calculate a climate change effect by 2050 which was on average over 15 EU member countries less than 3%. This points at the tendency of crop simulation models to project higher effects of climate changes than statistical approaches. One explanation for this is that crop-climate models primarily consider the effects of climate factors on crop growth and development. Effects of other factors such as weeds, pests and diseases are mostly not considered in these process-based models but are inherently part of statistical models. More comprehensive experimental data will be required to better evaluate such results (Rötter et al., 2011).

Positive effects of elevated atmospheric [CO_2] enhanced yields mainly for C3 crops to an extent which is consistent with data from FACE experiments (Ainsworth and Long, 2004; Long, 2006; Manderscheid and Weigel, 2007). Increasing [CO_2] concentration stimulated yields in wheat, barley, sugar beet and potatoes by 14.1%; 11.1%, 14.4% and 7.4% respectively, with small differences between years and regions. This is generally less pronounced than effects simulated in some earlier studies (e.g. Rötter & van Diepen, 1994).

However, most substantial positive yield changes were projected when considering the effect of technology development. This is consistent with earlier results (Ewert *et al*., 2005) but partly conflicting with analyses on winter wheat yields in Europe by Brisson et al (2010). The latter suggest that increased high temperature and drought stress may level off positive effects by technology development, especially in regions with currently highest potential yields and inputs. It is important to note that considering a technology effect not only increased the crop yields but also increased the differences between the scenarios. Projected yields were highest for the scenarios CCC A2 and 15GCM A1B and smallest for the scenario 15GCM B2, following the different assumptions made regarding technologies associated with these contrasting socio-economic and emission scenarios. In scenario family A (IPCC, 2001) it is assumed that agriculture undergoes highest intensification associated with more advanced technology development (e.g. breeding for higher yields and more efficient resource use) than in scenario family B. And for the latter, in B2, least progress in technology is assumed..

Clearly, considering the effects of climate change, atmospheric [CO_2] elevation and technology development separately had two main implications for our yield projections. On the one hand, the yield decreasing effect of changes in mere climatic factors was compensated and partially superseded when atmospheric [CO_2] elevation and technology development were taken into account. On the other hand, the yield differences between scenarios became greater when considering atmospheric [CO_2] elevation and technology development.

Finally, our results show some changes in variability under climate change (Fig. 11). However, these changes were mainly observed for maize and differed considerably depending on the region from decreasing to increasing variability under climate change. Other studies have reported increased yield variability as an impact of climate change in Europe (Jones *et al*., 2003; Porter and Semenov, 2005; Iglesias *et al*., 2010). However, in the present study we have not considered an approach to model the possible effects of extreme temperature stress or drought stress as increasingly referred to (Porter & Gawith, 1999, Porter and Semenov, 2005; Brisson et al., 2010; Asseng *et al*., 2011; Trnka et al., 2011). Modelling such effects is likely to result in a more pronounced yield variability under climate change as recently shown in a global assessment for four crops (Teixeira *et al*., this Issues; Rötter et al., in the Press).

4.2. Impacts on prices

Traditionally, assessments of climate change on food production and supply have been carried out by using process-based crop models, as we have done in the present study. When such crop model based yield estimates are available for larger regions or a continent, they are "usually combined with projections of future populations, trade and commodity prices to help us to estimate the future of the overall system (such as how much food we can grow in a warmer world)" (Rötter et al., 2011, p. 175). The AgriAdapt approach used relative yield changes under climate change to calculate effects on commodity prices. The analysis of price effects resulting from the implemented scenarios can be summarized by the following observations:

(1) Price impacts resulting from a reduced yield potential as a consequence of climate change are considerable strong but the impact of the macro-economic assumption (GDP/population) is even stronger.
(2) Price impacts on animal products are even more significant than those for crops, given that feed prices rise as well.
(3) Given this, the price impacts of the political environment, as simulated with WTO-liberalization assumptions, are quite modest.

Naturally, these results are subject to a number of model assumptions and simplifications. Firstly, the link of yields between the crop model and CAPRI was established in a quite explorative manner. There is plenty of room to improve this link, e.g. by aligning the management assumptions of the two models. Secondly, the scenario set up can be enhanced. For example the GDP in developing countries is based on the agricultural sector to a large extend. Increasing the GDP without assuming gains in the agricultural sector is therefore inconsistent. This is why the 25% and 50% GDP shock scenarios where also analyzed, since it may be more realistic to assume smaller GDP changes. Finally, CAPRI is very detailed on the

EU level, but the price reaction is very much dependent on how the rest of the world responds to the applied shocks. Since capacities do not play a role in the currents specification, e.g. the supply response potential of Brazil may be underestimated and consequently the price effects overestimated. Currently the representation of the rest of the world in CAPRI is changing in an ongoing project introducing the land use variable and a land market.

5. Summary and conclusion

We demonstrate the importance of crop model calibration for the assessment of climate change impacts on crops at regional scale. We find that considering regional differences of model parameters related to crop growth in addition to crop phenology can considerably improve yield simulations at continental scale (EU25). Calibration also effects simulations of climate change impacts on yields suggesting that projections with crop models can be improved if they are well calibrated.

Our results also show the importance of considering not only the effects of changes in weather variables, but also increased atmospheric [CO_2] and technology development for future yield estimations. Particularly, consideration of technology development can have substantial impacts on yield projections which need further investigation to reduce uncertainty in the assumptions about technology development. The considered crops respond differently to climate change which also poses the need to extent climate change studies to a larger range of crops.

The considered ensemble of climate change scenarios results in a range of yield responses which again is more pronounced when technology development is considered. As some of this technology development refers to yield improvements, future research on improving model calibration for large scale climate change studies will also need to address temporal changes in model parameters.

Such proposed extensions of our work may be further developed in the framework of the global AgMIP Initiative (www.agmip.org) that was launched in October 2010 and aims to establish a modelling framework “to provide more robust estimates of climate impacts on crop yields and agricultural trade, including estimates of associated uncertainties.” (Rötter et al., 2011).

Impacts of projected yield changes on prices cannot be neglected when analyzing climate change scenarios. It was shown that introducing yield shocks simulated by the calibrated crop models in an agricultural market model leads to significant price impacts and thus stimulation of management adjustments. The latter is not yet reflected in our analysis, but should be in future research, because a permanent situation of high prices would definitively accelerate technical progress in the agricultural sector und thus reducing the simulated yield loss induced by climate change. An iterative process between crop and market models would be in line with these considerations.

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