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Yield gap of winter wheat in Europe and sensitivity of potential yield to climate factors

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ABSTRACT: It is not clear whether the changing climate in Europe will be favourable for crop yield in the future. In this study, we quantified the yield gap for the year 2000 and analyzed the sensitivity of the rain-fed potential yield of winter wheat to changes in temperature, precipitation, and CO_2 across Europe. The ecosystem model ANTHRO-BGC was used to simulate potential yields; actual winter wheat yield data together with modelled potential yields were used to calculate yield gap. Artificial climate scenarios for the main climate factors used in sensitivity studies were generated according to climate scenarios from the IPCC 4th Assessment Report (AR4). We found that there is currently a large yield gap in Eastern Europe (around 6 t ha^{-1}), whereas in a few developed countries in Western Europe the harvested yield approaches potential yield (around 2 t ha^{-1}). Sensitivity analysis indicates that the rain-fed potential yield could increase by about 14% in Europe, under the assumption that the changes in temperature and precipitation will be the same as those projected for 2050 from AR4, and that CO_2 will increase from 380 to 550 ppm. This increase in projected potential yield is mainly due to fertilization effects caused by increasing atmospheric CO_2 concentrations (15% yield increase), whereas the projected changes in temperature and precipitation will negatively (–1%) affect the rain-fed potential yield in Europe.

KEY WORDS: Potential yield · Rain-fed potential yield · Yield gap · ANTHRO-BGC model · Winter wheat · Sensitivity analysis

1. INTRODUCTION

The issue of food production versus demand is of particular urgency in Europe because crop yields have been stagnating or even declining over the last 2 decades in many countries (Peltonen-Sainio et al. 2007, Brisson et al. 2010, Licker et al. 2013). Weather and climate influence agriculture directly, through a combination of changes in mean conditions and extreme events such as high temperature, drought,

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and heavy rain, and indirectly through sea-level rise and changes in the occurrence of pests and disease (Gornall et al. 2010, Lobell et al. 2013, Asseng et al. 2014). Current climate limitations on plant productivity will determine the future responses of plants to the warming climate (Churkina & Running 1998). In warm climate zones, crop yield is likely to decrease (Asseng et al. 2014) since higher temperatures can shorten the period for grain filling and may cause stress for plants, especially at the time of flowering and seed-set. At higher latitudes, crop yields are likely to increase as warmer temperatures allow for longer growing seasons (Parry et al. 2004, Jaggard et al. 2010). A 2°C temperature increase at mid-latitudes could increase wheat production by nearly 10%, whereas at low latitudes the same temperature change may decrease yields by nearly the same amount (Gornall et al. 2010). The anthropogenic increase in atmospheric CO_2 concentrations will also affect crop yields (McGrath & Lobell 2011). Plants benefit from elevated CO_2 concentrations through increases in photosynthesis and reductions in photorespiration (Ainsworth & Long 2005). Moreover, high CO_2 concentrations reduce stomatal conductance (Ainsworth & Rogers 2007), which may decrease canopy transpiration and improve soil and plant water status, and thus crop yield (Leakey et al. 2006, Bernacchi et al. 2007). The increase from present CO_2 concentrations to 550 ppm could potentially increase C_3 crop yields by 10–20%, and C_4 crop yields up to 10% (Long et al. 2004, Ainsworth & Long 2005). Even though increased CO_2 concentrations could increase water use efficiency, the concomitant temperature increase might counteract the beneficial effect of CO_2 on water consumption by increasing the rate of evapotranspiration (Jaggard et al. 2010). The combined effects of high temperature, elevated CO_2, and altered precipitation on crops are complex because of the interactions between different environmental drivers (Walker & Schulze 2008); further studies are required to explore the sensitivity of potential crop yields to climate change.

Future climate changes may be beneficial for wheat in some regions, but could reduce productivity in areas where the temperature is currently optimal for growth (Asseng et al. 2014). Winter wheat yield in southern Sweden, for instance, is predicted to increase by 10–20% by 2050 (Eckersten et al. 2001), whereas wheat yield in southern Australia is likely to decrease between 13.5 and 32% under most climate change scenarios (Luo et al. 2005). The impact of future climate change on crop production has been studied using crop models and climate change scenarios in some countries, e.g. Turkey (Ozdogan 2011), Belgium (Gobin 2010), and Italy (Dettori et al. 2011), and on a global scale (Balkovi et al. 2014, Rosenzweig et al. 2014). An assessment of the impacts of climate change on the potential yields of the main crops for rain-fed and irrigated agriculture in Europe, performed with the crop model WOFOST (van Diepen et al. 1989) and projected to the horizon in 2090, indicated positive effects of increasing CO_2 concentration for wheat yield (Supit et al. 2012). Potential yield is the yield of an adapted crop variety or hybrid when grown under favourable conditions without any growth limitations from water, nutrients, pests, or diseases (Lobell et al. 2009, van Ittersum et al. 2013, van Wart et al. 2013a). Under rain-fed conditions, where the water supply for crop production is not under the control of the grower, the water-limiting yield may be considered as the rain-fed potential yield for yield gap analysis, assuming other factors are not limiting crop growth (e.g. Wani et al. 2009). The objectives of the present study were (1) to quantify the potential yields of winter wheat *Triticum aestivum* L. in Europe from 1997–2003, and (2) to assess the sensitivity of potential yield to the predicted change in temperature, precipitation, and CO_2 to the horizon in 2050. An important aspect of the methodology was an update and validation of the ecosystem model ANTHRO-BGC (Ma et al. 2011) for use in achieving both objectives.

2. MATERIALS AND METHODS

We used the global crop dataset from Monfreda et al. (2008) as a reference dataset for actual crop yields. Actual yields of winter wheat were compared with the potential yields estimated with the ANTHRO-BGC for Europe from 1997–2003. The Modified Climate Research Unit (MCRU) climate dataset (Mitchell & Jones 2005, Chen et al. 2009) was used to drive the ANTHRO-BGC from 1948–2005.

2.1. The ecosystem model ANTHRO-BGC

The ANTHRO-BGC ecosystem model we used in this study was an updated version derived from the process-based model BIOME-BGC (Running & Coughlan 1988, Thornton 1998), which was originally designed to represent natural ecosystems such as forests and grasslands. The model operates at a daily time step and describes the dynamics of energy, water, carbon, and nitrogen in natural and managed ecosystems. It includes a newly developed, crop-specific phenology approach, calibrated in Europe (Ma et al. 2012). In the new phenology approach, the start and length of the growing season are estimated based on climate variables depending on carbon fluxes (in turn depending on air temperature, vapour pressure deficit, and photoperiod). Gross primary production is calculated using the Farquhar photosynthesis routine (Farquhar et al. 1980, De Pury & Farquhar 1997) separately for sunlit and shaded foliage. The routine includes the effect of CO_2 fertilization on plants (De Pury & Farquhar 1997). The eco-physiological parameters of ANTHRO-BGC for winter wheat were optimized using eddy covariance measurements of carbon and water fluxes in Europe for the period from 2005–2007 (Ma et al. 2011).

ANTHRO-BGC, which uses climate variables and atmospheric CO_2 concentration as the driving variables of plant physiological processes, is known to effectively reproduce the key components of the carbon and water cycles (i.e. gross primary production, net ecosystem exchange of CO_2, evapotranspiration) that are directly related to potential crop yield (Ma et al. 2011). The model was calibrated with observational eddy covariance, along with remotely sensed and phenological data from 7 cropland sites in Germany, Belgium, France, Switzerland, and Denmark (Ma et al. 2011, 2012). An assumption of this study was that the model, calibrated in Western European countries, can represent potential conditions in the rest of Europe. In the absence of detailed information on actual sowing dates (which depend on labour availability as well as economic and weather conditions; e.g. Sacks et al. 2010), sowing was set to occur 2 wk earlier than the onset of leaf greening (as estimated by the phenological model; Ma et al. 2012). We started with an analysis of the main climatic factors limiting the potential yield of winter wheat in Europe between 1997–2003 (see the Supplement at www.int-res.com/articles/suppl/c067p179_supp.pdf), followed by a quantification of the yield gap. The latter is defined as the difference between potential and actual yield, averaged over a given time period and spatial scale (Lobell et al. 2009, Boogaard et al. 2013). Finally, we performed a sensitivity analysis of the rain-fed potential yield to the assumed changes in temperature, precipitation, and atmospheric CO_2 concentration.

Daily weather inputs (maximum and minimum temperatures, vapour pressure deficit, precipitation, and global solar radiation), gridded at 0.25° resolution, were extracted from the MCRU dataset (Mitchell & Jones 2005, Chen et al. 2009) and used to drive ANTHRO-BGC from 1948–2005. The MCRU dataset covers all climate variables necessary for the simulation at a daily time scale for all of Europe within the boundaries 15° W to 60° E, and 30–75° N (which is not the case for other available datasets, e.g. the E-OBS dataset; http://eca.knmi.nl). The spin-up simulation was driven by climate data from the period 1960–1980, which were repeatedly used to bring soil carbon and nitrogen pools to near-equilibrium conditions.

The MCRU climate dataset was generated from the Climate Research Unit (CRU) dataset (which includes monthly climate variables), and the climate datasets from REMO or ECHAM5 (both providing variables with both monthly and daily resolutions). The procedure was based on the assumption of a linear relationship of monthly climate variables between CRU and REMO (Feser & Weisse 2001) or ECHAM5 (www.mpimet.mpg.de/en/science/models/echam.html) which can be used to estimate the daily climate variables for MCRU in 2 steps: (1) establishing the linear relationships between the monthly variables from CRU and REMO or ECHAM5 (Chen et al. 2009), and (2) generating the daily climate variables of MCRU according to these linear relationships and the daily climate data from REMO or ECHAM5.

Elevation and soil data (texture and depth) from a previous study (Vetter et al. 2008) were used in the model. Since we focused on the analysis of winter wheat, the C_3 crop cultivated area in Europe was assumed to be covered by winter wheat.

2.2. Potential wheat yields

The potential yield of wheat was calculated as the aboveground biomass estimated at physiological maturity multiplied by the harvest index, the latter set to 0.4 (Gervois et al. 2008, Lobell et al. 2010). We acknowledge that the fixed value of harvest index (which does not account for heat/cold damages that occur during pollination and ripening) could introduce uncertainties to the estimated potential yields over large regions (e.g. Farooq et al. 2011, Wang et al. 2015). However, it is difficult to dynamically estimate the harvest index while also considering spatial and temporal variations (Soltani et al. 2005, Kemanian et al. 2007, Gervois et al. 2008). Nevertheless, we showed that the simulated potential yield of winter wheat for the Netherlands compares well with existing observations (see Section 3.1).

To focus on the effects of climate on yield, we minimized the representation of human-related effects on yield increase. We removed virtually all nitrogen deficiency stresses to winter wheat by arbitrarily setting the nitrogen input rate at 2 kg N m^2 d^{-1}. Although wheat is a rain-fed crop in most countries, in order to explore whether water is a limiting factor for yield in Europe, yields from both potential and rain-fed conditions were estimated during the period 1948–2005, respectively removing and retaining the water limitations of croplands. Similarly to nitrogen, applying water at high rate (+20 mm per rainy day) ensured that water limitations were removed without adding problems caused by water excess (whose effect was not considered by the model).

2.3. Yield gap

To quantify the yield gap in Europe, the simulated potential wheat yields were compared against the actual yields extracted from the global crop dataset provided by Monfreda et al. (2008), which is a reference dataset for actual crop yields. This global crop dataset provides croplands on a 5 × 5 min (~10 × 10 km) latitude–longitude grid. For the purpose of simulations, we used ~0.25° grid points obtained by averaging 9 adjacent grid points. Specifically, we compared the average actual yield values for the period 1997–2003 against the estimated potential yield in 2000. We used the actual average yield data of Monfreda et al. (2008) because this dataset documents both average crop yields and crop cultivated areas for the period from 1997–2003 (which is not the case for the Eurostat dataset; http://ec.europa.eu/eurostat/). The average yield for 1997–2003 provides a reference point for comparison with the estimated potential yield for Europe because wheat yields have been stagnating in Europe since the 1990s and reached a plateau during 1997–2003 in most of the countries, with limited inter-annual variability (Brisson et al. 2010).

The yield gap (*Gap_Yp*) was calculated as the difference between the average estimated potential yield (*Yp*) from 1997–2003 and the average actual yield (*Y_stat*) during the same time period. The yield gap, in t ha^{-1} and in percent of the actual yield (*Gap_Yp_fraction*), was calculated following Eqs. (1) and (2) respectively for each grid cell:

$$Gap\_Yp = Yp - Y\_stat \tag{1}$$

$$Gap\_Yp\_fraction = \frac{Yp - Y\_stat}{Y\_stat} \times 100 \tag{2}$$

The same method was used to calculate the rain-fed yield gap.

2.4. Sensitivity testing

A total of 5 scenarios were generated for the sensitivity analysis of simulated potential yield of wheat to climate change factors.

The averaged maximum, median, and minimum values of changes in temperature and precipitation from the ensemble simulation of 21 Global Circulation Models within the A1B emission scenario (Christensen et al. 2007) were added to the historical observed temperature and precipitation values from MCRU for the period 1997–2003 for alternative scenarios. The A1B emission scenario is one of the storylines developed by the Special Report on Emissions Scenarios used in the IPCC 4th Assessment Report (IPCC 2007), which assumes a balance between the use of fossil fuels and alternative energy sources. Its climate output therefore constitutes only one of many possible future realizations. The changes in temperature and precipitation (Table 1) for 2050 (the time horizon set for this analysis) were created based on half of the projected change for the period 2080–2099, as given by Christensen et al. (2007). In this way, without running a climate change scenario analysis (which would be beyond the scope of this paper), the variability obtained with the altered scenarios constructed here is well within expected future climate variations. Different combinations of the minimum, median, and maximum changes in temperature and precipitation produced the 5 climate change scenarios (S1–S5) (Table 2) used in this study (for sake of simplification, other scenarios obtained with the median statistics of temperature and precipitation changes were not considered in the analysis). Another simplification is that the potential yields within these scenarios were obtained by running ANTHRO-BGC with the generated temperature and precipitation data and the historical records of global solar radiation and vapour pressure deficit for the period 1997–2003.

For all 5 climate scenarios (S1–S5), we increased the atmospheric CO_2 concentrations from 380 to 550 ppm in 2050 as reported in previous studies (Long et al. 2004, Ainsworth & Long 2005), so that the predicted effects of the increase in CO_2 concentration on potential yield could be compared to the reported experiment results.

Two groups of model simulations were run (Tables 1 & 2) in order to quantify the sensitivity of changing temperature, precipitation, and atmospheric CO_2 concentrations on the rain-fed potential yield. The first group of model simulations (G1) took into account only the change in temperature and precipitation; the second group (G2) additionally considered the effect of the assumed CO_2 concentration increase.

Table 1. Monthly temperature and precipitation changes (applied daily) for 2050 according to A1B emission scenario for 2080–2099 (IPCC 2007). Min., max., and median represent the minimum, maximum and median (50%) temperature and precipitation changes among the predicted results of 21 climate models used to predict climate change (Christensen et al. 2007). The monthly changes applied daily imply that the amount of change for temperature and precipitation on each day within the month was the same, but changes in temperature and precipitation for each month are different

	Temperature (°C)			Precipitation (%)		
	Min.	Median	Max.	Min.	Median	Max.
Northern Europe (48–75° N)						
Jan	1.3	2.15	4.1	4.5	7.5	12.5
Feb	1.3	2.15	4.1	4.5	7.5	12.5
Mar	1.05	1.55	2.65	0	6	10.5
Apr	1.05	1.55	2.65	0	6	10.5
May	1.05	1.55	2.65	0	6	10.5
Jun	0.7	1.35	2.5	−10.5	1	8
Jul	0.7	1.35	2.5	−10.5	1	8
Aug	0.7	1.35	2.5	−10.5	1	8
Sep	0.95	1.45	2.7	−2.5	4	6.5
Oct	0.95	1.45	2.7	−2.5	4	6.5
Nov	0.95	1.45	2.7	−2.5	4	6.5
Dec	1.3	2.15	4.1	4.5	7.5	12.5
Southern Europe and Mediterranean (30–48° N)						
Jan	0.85	1.3	2.3	−8	−3	3
Feb	0.85	1.3	2.3	−8	−3	3
Mar	1	1.6	2.25	−12	−8	−1
Apr	1	1.6	2.25	−12	−8	−1
May	1	1.6	2.25	−12	−8	−1
Jun	1.35	2.05	3.25	−26.5	−12	−1.5
Jul	1.35	2.05	3.25	−26.5	−12	−1.5
Aug	1.35	2.05	3.25	−26.5	−12	−1.5
Sep	1.15	1.65	2.6	−14.5	−6	−1
Oct	1.15	1.65	2.6	−14.5	−6	−1
Nov	1.15	1.65	2.6	−14.5	−6	−1
Dec	0.85	1.3	2.3	−8	−3	3

Table 2. Combinations of the minimum, median, and maximum changes in temperature and precipitation listed in Table 1 that were used to produce the 5 climate scenarios (S1–S5) in this study

	Temperature	Precipitation
S1	Min.	Min.
S2	Median	Median
S3	Max.	Max.
S4	Min.	Max.
S5	Max.	Min.

Rain-fed potential yields from the G1 and G2 model simulations were used to separately investigate the effects of the projected temperature and precipitation changes with and without increased atmospheric CO_2 concentrations. Average rain-fed potential yields simulated for 1997–2003 were used as a reference.

The yield change (*Y_change*) due to the changes in temperature and precipitation, in tons per hectare and in percent (*Y_change_fraction*), was calculated using Eqs. (3) and (4) for each grid cell:

$$Y\_change = Ypw\_S(i) - Ypw \quad (3)$$

$$Y\_change\_fraction = [Ypw\_S(i) - Ypw] / Ypw \times 100 \quad (4)$$

where *Ypw_S*(*i*) represents the average rain-fed potential yield for any scenario *S*(*i*) (with $i = 1, \ldots, 5$) for both groups (G1 and G2). *Ypw* represents the rain-fed average potential yield during 1997–2003. *Y_change* represents the change in the average rain-fed potential yield between the *S*(*i*) and reference simulation. Negative values indicate that yield decreased under the projected climate conditions.

3. RESULTS AND DISCUSSION

3.1. Yield gap between 1997–2003

Spatial patterns of yield gap were rendered out (using a smoothing option) in the form of pixelated European maps (0.25° grid resolution) for the period between 1997–2003 (Fig. 1). On average, the estimated yield gap was 5.22 t ha^{-1} (Fig. 1a), while the rain-fed yield gap was smaller (2.4 t ha^{-1}: 68% of potential yield; Fig. 1b). The lower value for the rain-fed yield gap points to the fact that water is an important limiting factor for crop production in some regions of Europe (EEA 2009). However, negative yield gaps occurring in some areas indicate that in these areas, the water supply is less limiting than that assumed in the simulations.

The average European yield gap of 5.22 t ha^{-1} calculated here is higher than the yield gap of 2–4 t ha^{-1} estimated by Boogaard et al. (2013) with the crop model WOFOST, which was calibrated against experimental data from wheat crops in the 1980s. This underestimation of the potential yield might be due to model calibration against lower wheat yields than in 1997–2003 (Fischer & Edmeades 2010), or failing to consider adaption strategies of farmers (Balkovič et al. 2014, Moore & Lobell 2014). Using Netherlands as an example, the potential yield of the current win-

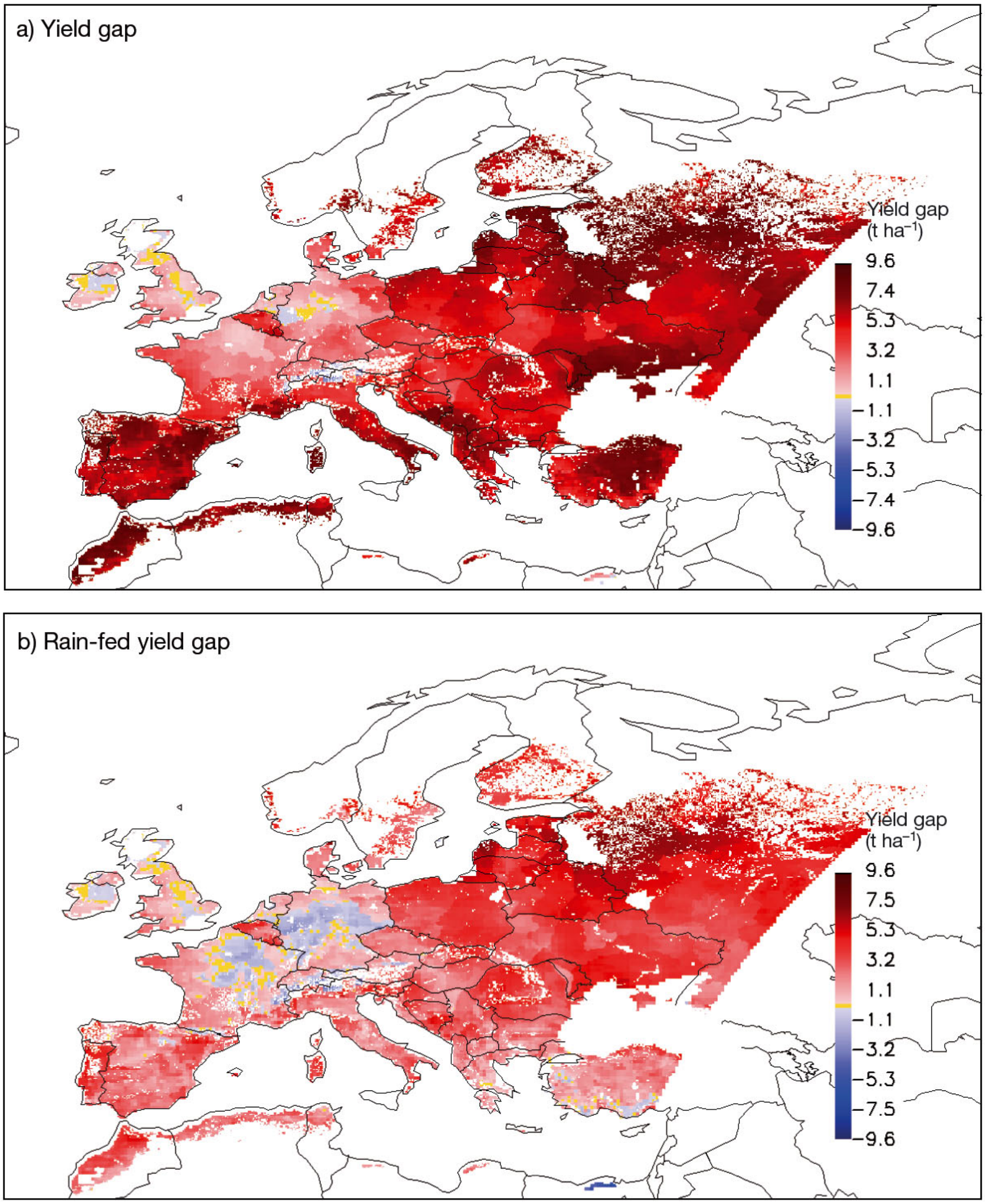

Fig. 1. Spatial distribution patterns of yield gaps in Europe between 1997–2003: (a) yield gap calculated as the difference between the averages of potential and actual yield, and (b) rain-fed yield gap calculated as the difference between the averages of the rain-fed potential and the actual yield

ter wheat variety determined from experiments is 9.6 t ha^{-1} (Boogaard et al. 2013). WOFOST underestimated this potential yield of winter wheat (8.7 t ha^{-1}; Boogaard et al. 2013), while our estimation of 9.2 t ha^{-1} is closer to the experimental value.

The estimated yield gap in Eastern Europe was larger than in Western Europe (Fig. 1) and the harvested yield in several developed countries, such as Germany and France, was close to the potential yield (Fig. 1). Our results, along with those of a previous study (van Wart et al. 2013b), suggest that there is no substantial difference between Eastern and Western Europe in terms of potential yield production. The analysis of actual yields and management data indicates that wheat growth can be limited by nitrogen deficiency in Eastern Europe (Mueller et al. 2012). As a consequence, the yield gap difference between Eastern and Western Europe is mainly due to higher actual yields in Western Europe, where agricultural management is more advanced. This means that the yield production in Eastern Europe holds a potential for improvement in the future, with higher rates of fertilization and other advanced management techniques.

3.2. Sensitivity of rain-fed potential yield to climate change

The sensitivity to projected temperature and precipitation changes of the rain-fed potential yield were explored with and without the effects of the CO_2 concentration increase. An assessment of the potential yield was not considered because wheat crops grown with water limitations respond more strongly to high CO_2 concentrations than water-supplied crops (Gifford 1979).

3.2.1. Sensitivity of rain-fed potential yield to changes in temperature and precipitation

The simulation results showed that the rain-fed potential yields for Europe would increase by 0.02 t ha^{-1} (+0.31 %) and by 0.06 t ha^{-1} (+1 %) in the S3 and S4 scenarios, respectively (Fig. 2). A decrease of 0.24 t ha^{-1} (–4.05 %), 0.08 t ha^{-1} (–1.37 %), and 0.27 t ha^{-1} (–4.58 %) was predicted for the S1, S2 and S5 scenarios, respectively (Fig. 2). This yield change is relative to the reference rain-fed potential yield of 5.93 t ha^{-1}, which is the average for Europe during the period 1997–2003.

The strongest yield decrease (S5) and the greatest yield increase (S4) can be attributed to both the high sensitivity of the model to temperature and the positive effects of water supply on rain-fed potential yield. S5 assumes the largest increase in temperature and the lowest precipitation in 2050, whereas in contrast, S4 postulates the lowest temperature and highest precipitation in 2050. This result for Europe is in agreement with the finding that temperature increases cause grain yield reductions in cereals worldwide (Lobell & Field 2007, Asseng et al. 2014, Bassu et al. 2014). With respect to the effects of both temperature and water on plant physiology, the differences between S5 and S4 are as would be expected.

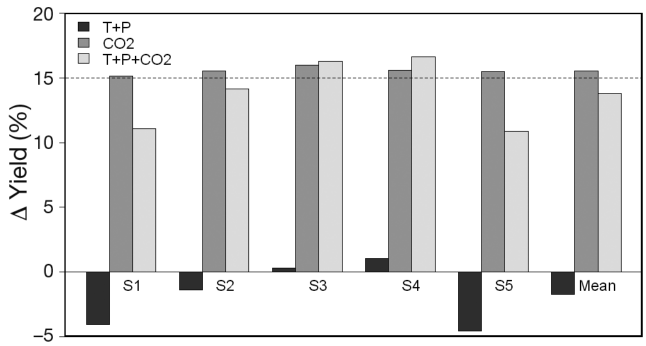

Fig 2. Change in the rain-fed potential yield (%) of Europe between climate scenarios S1–S5 and a reference simulation. Yield changes are calculated as differences between the estimated yields within climate scenarios and the reference (mean of 1997–2003). The differences were weighted with the cultivated area for each pixel as shown in Fig. 1. Black bars: response to changes in temperature and precipitation (T+P) only; dark grey bars: response to elevated CO_2 concentration (CO_2) only; light grey bars: response to the 3 factors together (T+P+CO_2). Horizontal dashed line is for reference to compare bar height

The rain-fed yield changes in response to the changes in temperature and precipitation show a clear spatial pattern (Fig. 3). When the different scenarios are considered, the greatest increase in rain-fed potential yield was seen in the relatively cool region of northern Europe, and the strongest decrease was estimated for southern Europe. This spatial pattern is consistent with the correlation between rain-fed potential yield and temperature as discussed in Section S2.3 in the Supplement at www.int-res.com/articles/suppl/c067p179_supp.pdf, and in previous studies (e.g. Asseng et al. 2014, Rosenzweig et al. 2014).

The spatial patterns of rain-fed potential yield in response to climate change, as shown in this study, are corroborated by several studies at the regional and site level. For autumn-sown crops (such as winter wheat), the impact of climate change on yield has been shown to be geographically variable (Olesen et al. 2007, Balkovi et al. 2014). These authors expected yields to strongly decrease across large parts of southern Europe (e.g. north of Portugal and Spain), but to increase in the cooler, northern areas, where presently rather low temperatures and levels of radiation are crop-growth limiting factors. Other studies also support the expectation of increased future crop yields in the northern parts of Europe, while large yield reductions are projected for the Mediterranean and the south-western Balkan regions as well as southern parts of European Russia (Olesen & Bindi 2002, Maracchi et al. 2005, Alcamo et al. 2007).

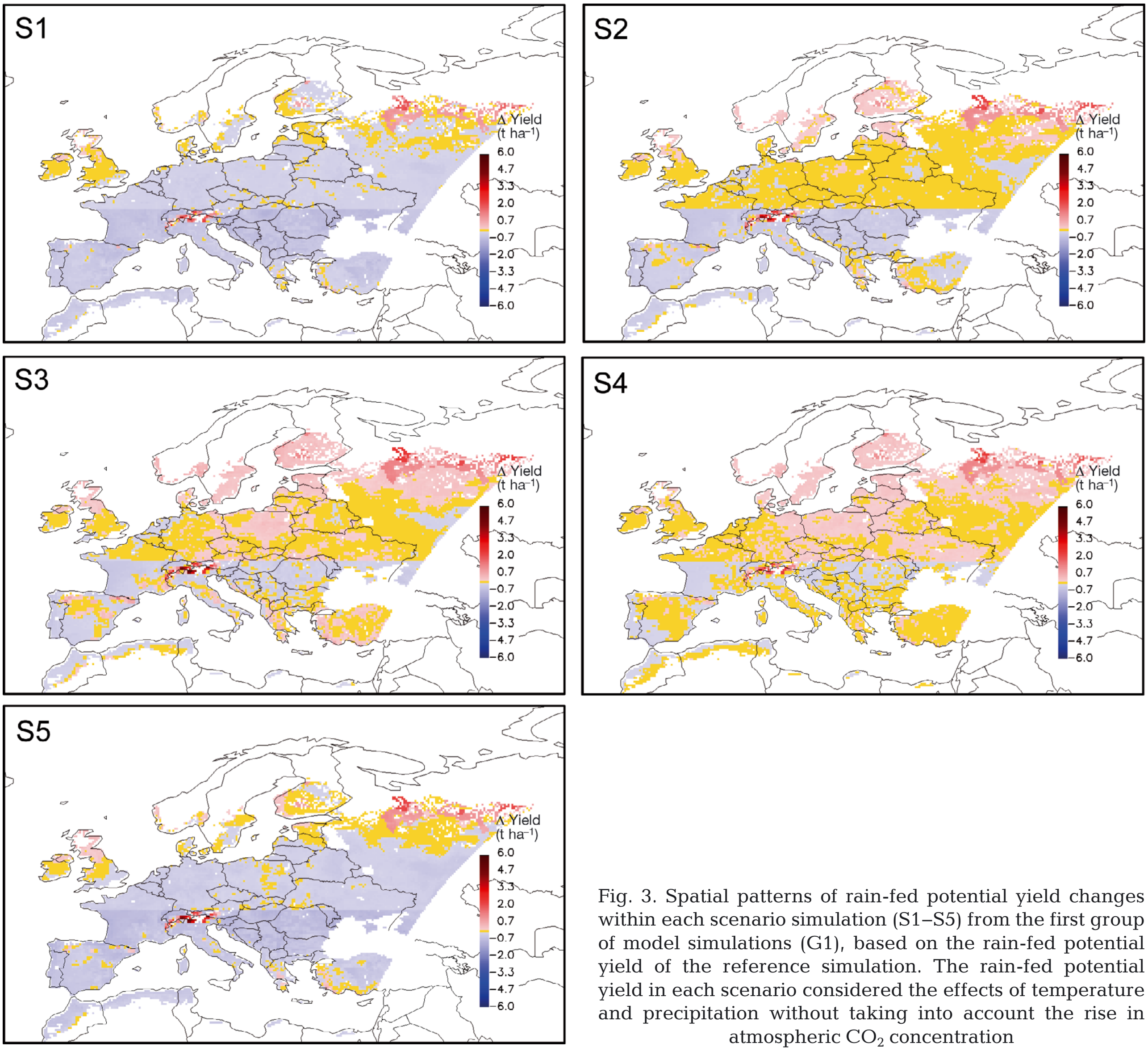

Fig. 3. Spatial patterns of rain-fed potential yield changes within each scenario simulation (S1–S5) from the first group of model simulations (G1), based on the rain-fed potential yield of the reference simulation. The rain-fed potential yield in each scenario considered the effects of temperature and precipitation without taking into account the rise in atmospheric CO_2 concentration

3.2.2. Sensitivity of rain-fed potential yield to temperature, precipitation, and atmospheric CO_2 concentration

Taking the impact of increased atmospheric CO_2 concentrations into account, we estimated the rain-fed potential yield to increase by 11–17% (depending on the scenario) for Europe (Figs. 2 & 4). Considering that the likelihood of any given scenario is subject to a degree of uncertainty (which makes it difficult to develop the most likely one), we treated all scenarios (S1–S5) as being equally likely to occur. Even though the likelihood of Scenario S2 (median temperature and median precipitation) would be higher than the other min./max. combinations, we represented the central tendency of all the scenarios (as in similar studies, e.g. Eitzinger et al. 2013). In this way, as an average for Europe and for the 5 scenarios, rain-fed potential yield increased by about 15% solely due to the increase in atmospheric CO_2 concentration to 550 ppm. The effects of increasing CO_2 concentrations on crop yields predicted here are in agreement with previous studies, which estimated that a comparable rise in atmospheric CO_2 concentrations could increase C_3 crop yields by 10–20% on average (Long et al. 2004, Ainsworth & Long 2005). The increase in rain-fed potential yield of winter wheat (14%) within the scenarios assessed in this study is slightly lower than the comparable estimates of 19% by Supit et al. (2012) (set to an average

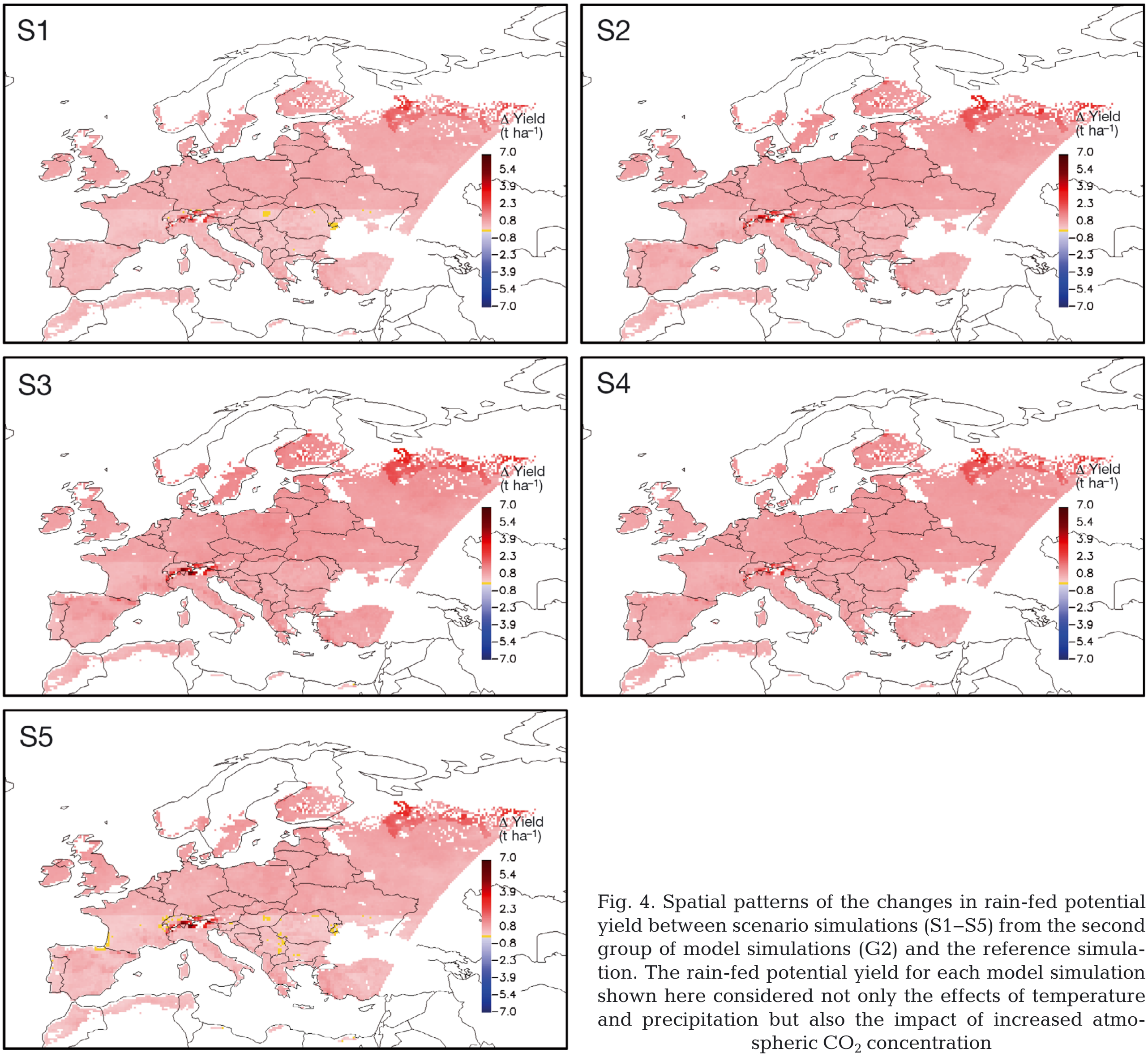

Fig. 4. Spatial patterns of the changes in rain-fed potential yield between scenario simulations (S1–S5) from the second group of model simulations (G2) and the reference simulation. The rain-fed potential yield for each model simulation shown here considered not only the effects of temperature and precipitation but also the impact of increased atmospheric CO_2 concentration

value). The differences arise from the following points. (1) ANTHRO-BGC includes a dynamic phenology model for crops (Ma et al. 2012) instead of assuming fixed sowing dates as in WOFOST (Supit et al. 2012). Therefore, the growing season of winter wheat simulated by ANTHRO-BGC follows changes in weather conditions over a period of years. The length of the growing season has significant impacts on plant production (Churkina et al. 2005, Ma et al. 2012). In fact, an earlier growing season with the less favourable solar radiation conditions in early spring may limit crop productivity. (2) Although Supit et al. (2012) used data from different climate models as inputs for WOFOST, their model did not take into account the ability of plants to adapt to the changes in climatic conditions by modifying their morphology and physiology. This introduces uncertainty in yield estimation since, according to the projection of climate models, the frequency of adverse weather events are expected to increase (Trnka et al. 2014), but the plants' adaptability to such changing conditions were not taken into account.

The rain-fed potential yield within the projected scenarios is predicted to increase by about 14 % when the effects of the projected temperature and precipitation change as well as the elevated CO_2 concentration are taken into account. This is the result of a 15 % increase due to increasing CO_2 concentration and a 1 % decrease due to future projected temperature and precipitation changes.

4. CONCLUSIONS

The spatial distribution of the yield gap is helpful to show where and how yield production can be improved, while the estimation of the future potential yield gives an idea about the future food supply (Balkovi et al. 2014). In this study, a larger yield gap was estimated for Eastern than for Western Europe. Our simulated potential yield (ca. 9.2 t ha^{-1}) and rain-fed potential yield (ca. 8.5 t ha^{-1}) was closer to the actual yield of winter wheat (ca. 7 t ha^{-1}) in several developed countries, such as Germany and France during 1997–2003. The rain-fed potential yield of winter wheat could increase by 11–17% in Europe within the projected climate scenarios as a result of changes in temperature, precipitation, and CO_2 concentration. We estimated that the CO_2 concentration increase from 380 to 550 ppm could alone cause an average increase of 15% in rain-fed potential yield. In contrast, the average changes in temperature and precipitation may have slightly negative effects (−1%) on the rain-fed potential yield in Europe. Precipitation and radiation were the most limiting climatic factors for winter wheat growth in Europe (as discussed in the Supplement, www.int-res.com/articles/suppl/m067p179_supp.pdf). An earlier start to the growing season due to warmer spring temperatures, combined with still relatively low solar radiation at that time likely resulted in lower yields for some parts of Europe. We acknowledge that the uncertainties in modelled yields may be substantial, as they originate from the model structure and parameterization as well as from forcing agents (Jung et al. 2007). A measure of the central tendency of a population of yield values estimated with multiple crop models can result in a better agreement with observed yields compared to any single model prediction (e.g. Asseng et al. 2013, Challinor et al. 2014, Rosenzweig et al. 2014). Moreover, the objective of this study was to run a sensitivity analysis on 2 climate variables (that is, a simulation exercise to assess the sensitivity of the crop model to changes in temperature and precipitation), not a climate change impact study. Therefore, it is mainly useful for ANTHRO-BGC users, but can be of interest for members of the modelling community who are performing simulation experiments over Europe, in that the results illustrated here for ANTHRO-BGC can be compared with the sensitivity of other models. An interesting perspective would be to superimpose the climate changes projected by climate models with the emission scenarios used by the 5th IPCC Assessment Report (IPCC 2013), to the curr ent sensitivity analysis and extend the analysis to global gridded crop modelling to construct envelopes of simulated yield.

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