Impacts and Uncertainties of +2°C of Climate Change and Soil Degradation on European Crop Calorie Supply

Juraj Balkovič[1,2], Rastislav Skalský[1,3], Christian Folberth[1], Nikolay Khabarov[1], Erwin Schmid[4], Mikuláš Madaras[5], Michael Obersteiner[1], and Marijn van der Velde[6]

[1]International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Schlossplatz 1, A-2361 Laxenburg, Austria, balkovic@iiasa.ac.at, skalsky@iiasa.ac.at, folberth@iiasa.ac.at, khabarov@iiasa.ac.at, oberstei@iiasa.ac.at

[2]Department of Soil Science, Faculty of Natural Sciences, Comenius University in Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovak Republic, balkovic@fns.uniba.sk

[3]National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Gagarinova 10, 827 13 Bratislava, Slovak Republic, r.skalsky@vupop.sk

[4]Institute for Sustainable Economic Development, University of Natural Resource and Life Sciences, Vienna, Feistmantelstrasse 4, 1180 Vienna, Austria, erwin.schmid@boku.ac.at

[5]Crop Research Institute, Drnovská 507/73, 161 06 Prague, Czech Republic, madaras@vurv.cz

[6]European Commission, Joint Research Centre, Via Enrico Fermi 2749, 21027 Ispra, Italy, marijn.van-der-velde@ec.europa.eu

Corresponding author: Juraj Balkovič (balkovic@iiasa.ac.at)

Key Points:

- Quantification of the biophysical consequences up to +2°C of global warming on calorie supply from main crops in Europe
- Mostly positive change in calorie supply was estimated, with uncertainty due to crop management intensification, temperature, and CO_2 effect
- Soil degradation could undermine climate-related benefits in Eastern and North-Eastern Europe

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2017EF000629

Abstract

Even if global warming is kept below +2°C, European agriculture will be significantly impacted. Soil degradation may amplify these impacts substantially and thus hamper crop production further. We quantify biophysical consequences and bracket uncertainty of +2°C warming on calories supply from ten major crops and vulnerability to soil degradation in Europe using crop modelling. The Environmental Policy Integrated Climate (EPIC) model together with regional climate projections from the European branch of the Coordinated Regional Downscaling Experiment (EURO-CORDEX) were used for this purpose. A robustly positive calorie yield change was estimated for the EU Member States except for some regions in Southern and South-Eastern Europe. The mean impacts range from +30 Gcal ha^{-1} in the north, through +25 and +20 Gcal ha^{-1} in Western and Eastern Europe, respectively, to +10 Gcal ha^{-1} in the south if soil degradation and heat impacts are not accounted for. Elevated CO_2 and increased temperature are the dominant drivers of the simulated yield changes in high-input agricultural systems. The growth stimulus due to elevated CO_2 may offset potentially negative yield impacts of temperature increase by +2°C in most of Europe. Soil degradation causes a calorie vulnerability ranging from 0 to 80 Gcal ha^{-1} due to insufficient compensation for nutrient depletion and this might undermine climate benefits in many regions, if not prevented by adaptation measures, especially in Eastern and North-Eastern Europe. Uncertainties due to future potentials for crop intensification are about two to fifty times higher than climate change impacts.

1 Introduction

Climate change and soil degradation are among the major threats to agriculture and food security (Lal et al., 2007; Meersmans et al., 2016; Tilman et al., 2002) and recognized as such by farmers across Europe (Olesen et al., 2011). Following the Paris climate agreement, 193 nations have committed to keep the global average warming well below 2°C relative to preindustrial temperatures and pursue efforts to limit the temperature increase to 1.5°C. Recent climate projections indicate that Europe will warm at a faster rate than the global average, and a +2°C of global warming will bring a significantly changed climate to Europe (Vautard et al., 2014). For example, Northern and Eastern Europe in winter and Southern Europe in summer will likely experience warming up to +3°C, with an increase in winter precipitation in Central Europe and an overall increase of precipitation over Northern Europe. The trends and amplified weather variability characterizing this future climate will bring challenges to Europe, one of the largest producers of agricultural goods.

To inform mitigation efforts, consequences of holding global warming below +2°C should be quantified. For example, keeping globing warming at a low level may lower future damages in the Mediterranean region, but it may constrain potential benefits from warming in the north (Müller et al., 2015). On one hand, increased temperature will accelerate crop development and shorten crop growth periods, thus potentially reducing crop yields in the productive temperate and Mediterranean Europe (Asseng et al., 2015; Lobell & Field, 2007; Supit et al., 2010). More intense heat waves and droughts, together with heavy rains, hail, floods, pests and diseases, will further hamper crop productivity. On the other hand, carbon dioxide (CO_2) fertilization has been recognized to compensate part of the negative effects and possibly even offset productivity losses, although the magnitudes of these effects are uncertain and subject to debate (Ewert et al., 2007; Kimball, 2016; Leakey et al., 2009; Long et al., 2006). Since experimental data to estimate physiological impacts of changing climate are generally lacking or difficult to collect and evaluate at large scales (Asseng et al., 2013, 2015), crop models are increasingly used to support climate change impact assessments (Asseng et al., 2015; Rosenzweig et al., 2014).

An increasing number of studies describe climate change impacts on crops, but the impacts of soil degradation have received much less attention, even though combatting continuing degradation is of utmost importance (Bindraban et al., 2012; Montanarella, 2015). Soil with a lowered capability to store and release water and nutrients can provide only little relief to crops coping with impacts from climate change. Indeed, healthy soils can help crops to cope better with increased climate variability (Tubiello et al., 2007). Continuous cropping can deplete soil fertility due to inadequate replacement of nutrients harvested with produce or lost through leaching, erosion, and atmospheric emissions. Most of the processes responsible for soil degradation, including soil organic matter mineralization and erosion, are enhanced by higher temperature and more intense precipitation. It has been estimated that almost 40% of the total agricultural land in Europe is prone to soil degradation at a moderate or higher level of severity (Lal, 2008).

Interactions and transfer of uncertainty through the climate to crop model chain introduce a concern for climate change impact studies (Asseng et al., 2013). The uncertainty encompasses, inter alia, inherent uncertainty in climate projections (Challinor et al., 2009), crop response to increased temperature and elevated atmospheric CO_2 concentration (Asseng et al., 2015; Kimball, 2016; Long et al., 2006), soil heterogeneity (Folberth, Skalský, et al., 2016), and model complexity and parameterization (Challinor et al., 2009). Advances in crop management (e.g. fertilization and irrigation, technological innovations and breeding) together with expansion of cropland (Ewert et al., 2005; Jaggard et al., 2010; Smith et al., 2010) contribute additional uncertainty for future projections. Having this in mind, quantification of uncertainties is therefore an important endeavour in large-scale impact studies such as ours.

In this study we quantify biophysical impact of global warming as high as +2°C on calorie supply from ten major crops and its vulnerability to soil degradation in the European Union (EU) Member States. To our knowledge, such large-scale analysis is still lacking despite a growing number of impact studies in the agricultural sector. An ensemble of the most recent regionally-downscaled climate change projections from the European branch of the Coordinated Regional Downscaling Experiment (EURO-CORDEX) is used, together with the Environmental Policy Integrated Climate (EPIC) crop model, to capture inherent uncertainties due to climate simulation. The uncertainties due to EPIC crop modelling are quantified via an uncertainty analysis with varying model assumptions and parameters.

First, we estimate, at a regional scale, the ranges and robustness of biophysical impacts on the combined crop-derived calorie yield. Second, we disentangle the vulnerability to soil degradation in terms of soil loss, depletion of plant nutrients and soil organic carbon since these are among the major threats to crop production, especially in regions with less developed agricultural systems. Finally, we bracket projected calorie yield uncertainties related to 1) future crop intensification possibilities, 2) increased temperature and elevated CO_2 effects, and 3) uncertainty in soil degradation modelling.

2 Data and Methods

2.1 Gridded crop model

A gridded pan-European EPIC model was used in this study (Balkovič et al., 2013). The model was built by coupling the field-scale model EPIC v. 0810 (Izaurralde et al., 2006, 2012; Williams, 1995) with large-scale data on environmental conditions and crop management practices in Europe (Table 1).

In EPIC, potential crop growth is calculated daily from intercepted photosynthetically active radiation using the energy-to-biomass conversion approach modified for vapour pressure deficit and atmospheric CO_2 concentration effect (Monteith, 1977; Stockle et al., 1992). The potential daily increase is adjusted to an actual biomass increase if the potential demand for water or nutrients exceeded actually available supply, or the temperature goes beyond the optimal range. The root growth is constrained by soil strength or aluminium toxicity. Plant phenological development, including leaf growth, plant nutrients concentration, partitioning of biomass among roots and shoots as well as yield formation are defined by heat units (in °C) accumulated over the growing season. Since soils are storing, cycling and providing nutrients and water for crops in EPIC, dynamic soil processes ranging from soil hydrology to organic matter and nutrient cycles are simulated (Izaurralde et al., 2006, 2012; Williams, 1995). EPIC allows simulations with a static soil profile, when all soil properties except for plant-available nutrients and water are re-initialized at the beginning of each year, or with a dynamic soil profile when soil properties are continuously simulated over time. EPIC's processes relevant for assessment of climate change impact on crops were summarized in the supplementary information of Folberth, Skalský, et al. (2016) based on the aforementioned references.

The bio-physical EPIC v.0810 model was coupled with ArcGIS and a gridded modelling framework was built by integrating EU-wide geospatial data on soils, terrain, land cover, watersheds, administrative units and regionalized crop management practices (Table 1) with 1-km grid. Redundant grids were clustered into simulation units (SimU) upon which the model was run. The model was designed to simulate regional crop yields as driven by gridded inputs on weather, site and soil properties, crop management scenarios and atmospheric CO_2 concentration, and was extensively evaluated by Balkovič et al. (2013).

Ten major European crops, namely winter wheat, winter rye, spring barley, grain maize, rice, winter rapeseed, soy bean, sunflower, sugar beet and potatoes, were simulated for 25 Member States of the EU. We excluded Malta, Cyprus and Croatia from the analysis due to lack of input data. Regional differences in crop varieties characterized by different growth period lengths follow the climatic stratification in the EU as described by Balkovič et al. (2013). Planting and harvesting dates were scheduled automatically based on heat unit accumulation, while potential heat unit requirements (PHU) were constant during the course of the simulation. Automatic harvest was scheduled at 110% (cereals and potatoes) and 115% (grain maize, rapeseed, sunflower and soy bean) of the PHU to enable flexible harvesting and to take post-maturity drying of crops on the field into account. All crops were simulated in mono-crop rotations on all the available cropland. Crop rotations and present-day harvested areas were not included since this information is generally lacking at the target resolution and this pattern may change in the future. Rice was simulated only in Bulgaria, France, Greece, Hungary, Italy, Portugal, Romania and Spain. Although EPIC's ability to simulate historical yields was extensively validated for some crops by Balkovič et al. (2013), we extended this comparison to reported yields to include all crops from this study in the Supporting Information (Text S1, Figure S9, and Table S4). Parameters used to describe crop's growth characteristics and their response to increased atmospheric CO_2 are summarized in Table S5.

2.2 Climate data

A regional ensemble of bias-corrected EURO-CORDEX climate change simulations (Jacob et al., 2014) developed in the Quantifying Projected Impacts Under 2°C Warming project (IMPACT2C, http://impact2c.hzg.de) was integrated in the crop modelling framework to have a robust projection of future warming in Europe. In our study, the projections meet the +2°C threshold when their driving global climate models reach the +2°C threshold globally. This threshold is reached when the 30-year running mean temperature calculated from the base period 1971–2000, plus the observed pre-industrial warming before this period, exceeds the +2°C threshold (Vautard et al., 2014). Accordingly, 30-year periods around the year when the +2°C warming was reached and the base period of 1971–2000 were evaluated throughout the paper. A total of five moderate emission RCP 4.5 projections were used (Table 1) since most of the low emission RCP2.6 simulations in EURO-CORDEX do not reach +2°C at all and the high emission RCP 8.5 scenarios are not compatible with the +2°C mitigation target. Given the selected RCP 4.5 projections and periods when the +2°C threshold is reached, atmospheric CO_2 concentration increases from about 360 ppm around the year 2000 up to concentration of 470 to 580 ppm at the +2°C threshold.

<TABLE 1>

2.3 Crop management scenarios

A total of three crop management scenarios were designed to analyse biophysical impacts of +2°C on calorie yields (Table 2).

(1) The business-as-usual (BAU) scenario represents fertilization and irrigation practices around the year 2000, and serves as a baseline for future projection in this study. Fertilization intensity was estimated by computing fertilizer balances for sub-national statistical regions (NUTS2). Crop-specific annual nitrogen (N) and phosphorus (P) fertilizer application rates were estimated from NUTS2 livestock numbers and excretion coefficients as well as commercial fertilizer consumption from EUROSTAT (http://ec.europa.eu/eurostat). Fertilizer demands at NUTS2 level were calculated using crop and forage yields and acreages from EUROSTAT as well as nutrient uptake coefficients (Balkovič et al., 2013). Annual P and N fertilizer amounts comprise both mineral and organic fertilizers expressed in kg of mineral N and P equivalent per hectare and crop. Phosphorus was applied as a rigid amount together with tillage operation before sowing, while N amount was used as an upper application limit for automatic fertilization splitting in EPIC. Single N applications were triggered automatically based on crop requirements. As a rule, 80% of the amount applied in the previous season was applied at the beginning of the following season, while next applications were triggered using the same 80% rule always when crop requirements exceeded soil supply, until the annual limit was reached. As a results, N fertilizer is commonly split in two or three applications. Irrigation extent as well as area share of irrigated crops were taken from the European

Irrigation Map (Wriedt et al., 2009). Since spatial data for crop-specific water application volumes are lacking, we assume that irrigated crops are supplied with ample water quantities to eliminate water stress (Folberth, Skalský, et al., 2016; Rosenzweig et al., 2014). Irrigation water was supplied to refill soil water content to its field capacity each time when crop stress occurred, while the upper annual limit was set to 1000 mm crop^{-1} (Balkovič et al., 2013, 2014). Rice was simulated only under full irrigation, but without excessive water applications typical for paddy cultivation. The BAU calorie yield was calculated as an average of rainfed and irrigated yields weighted by crop-specific share of irrigated and rainfed cropland (Section 2.4).

(2) The scenario P1 is designed to estimate the potential calorie yields assuming unconstrained intensification of the existing rainfed and irrigated production systems. Existing irrigation facilities identified by the EIM (Table 1) were allocated to all crops to fully compensate for water deficit as described above. Phosphorus fertilizer was supplied automatically in sufficient quantity to entirely avoid P stress (Gerik et al., 2013). The maximum annual application rate of 250 kg N ha^{-1} crop^{-1} was used to eliminate nitrogen stress on all cropland. To estimate N fertilization needed to achieve the P1 potential yield, the N application rate was distributed automatically by smaller quantities when crop nitrogen stress occurred, resulting in N applications lower or equal 250 kg ha^{-1} crop^{-1}. The final calorie yield was calculated while the fraction of area equipped for irrigation was used as a weight treating crops equally. Neither pest nor disease effects were considered.

(3) The P2 scenario assumes sufficient fertilization and irrigation in every SimU of European cropland, irrespective of existing irrigation infrastructure. This scenario provides calorie yield estimates close to the biophysical potential. Similar to the above scenarios, all crops except for rice were simulated on all the available cropland to account for possible shifts in future harvested areas. Pests and diseases were not considered.

All crop management scenarios were simulated with constant soil profiles (*con*), where all soil variables other than readily available nutrients (nitrogen and phosphorus) and soil water content were re-initialized each year and soil erosion was not considered. These simulations allow the assessment of climate change impacts independently from soil degradation. Besides simulations with constant soil profiles, dynamic soil profiles (*dyn*) together with the BAU crop management scenario were used to account for future vulnerability to soil degradation (see Section 2.5). The *dyn* soil profile scenario includes water erosion processes and transient simulation of main soil variables, including soil organic carbon and nitrogen, nutrient and carbon loss with erosion, bulk density, and soil depth. More details can be found in Text S3 in the Supporting Information.

All simulations were carried out assuming conventional tillage, consisting of two cultivation operations and moldboard ploughing prior to sowing and an offset disking after harvesting of cereals. Two row cultivations during the growing season were assumed for maize and one ridging operation for potatoes. We assume that 20% of crop residues are removed in case of cereals (excluding maize), while no residues are harvested for other crops (Köble, 2014). Aboveground crop residues were recycled by a 15 cm deep plough with high mixing efficiency.

<TABLE 2>

2.4 Spatial aggregation of outputs and impact metrics

2.4.1 Aggregation of model outputs

The simulations were carried out from 1971 till the end of the respective +2°C periods (see Table 1) with all climate projections and crop management scenarios. Model calculations were preceded by a 50-year spin-up simulation with repeated historic weather to equilibrate initial soil properties with respect to the BAU management specifications and local climate. Gridded crop yields (y) were converted from dry to fresh matter and subsequently calculated as weighted average of rainfed and irrigated production with Eq (1). The y values were summed across all crops and converted to the combined calorie yield (Y) by Eq (2). Conversion factors for dry-to-fresh matter yield as well as calorie content per unit of fresh matter yield (g) are summarized in Table S1. The calorie yields were regionalized for each year as an arithmetic average of all cropland belonging to either a NUTS2 or a country region.

$$y_{t,p,s,c} = \left(1 - f_{c,p}\right) \cdot y(r)_{t,p,s,c} + f_{c,p} \cdot y(i)_{t,p,s,c} \qquad (1)$$

$$Y_{t,p,s} = \sum_{c=1}^{k} g_c \cdot y_{t,p,s,c} \qquad (2)$$

where $y_{t,p,s,c}$ is crop fresh matter yield (in t ha^{-1}) of crop c, in grid p, climate scenario s, and the t-th year, $y(r)$, $y(i)$ stand for yield simulated under rainfed and irrigated conditions, respectively, $f_{c,p}$ is the fraction of irrigated area of the c-th crop in the p-th grid, $Y_{t,p,s}$ is the aggregated calorie yield expressed as a sum of all simulated crops (in Gcal ha^{-1}) in grid p, climate scenario s, and year t, k is the number of crops and g_c denotes calorie content per unit yield of the c-th crop.

2.4.2 Impact metrics

Unless stated otherwise, all biophysical impacts are expressed as absolute or relative yield change between the reference period 1971–2000 with BAU crop management (baseline) and the respective estimates for the +2°C period. Differences between mean yield values were statistically evaluated using the two-tailed paired *t*-test where appropriate, while linear regressions were tested by the *F*-test. All statistical analyses and plotting were done in R (R Core Team, 2016). In Section 3.2, the sums of daily temperature and precipitation over the growing seasons of all crops were calculated to support the analysis therein.

The impact robustness (*R*) across climate projections was assessed as a fraction of EPIC realizations with a positive change in calorie yield with respect to the total number of realizations calculated for NUTS2 regions. Therefore, the robustness accounts for SimU-level agreement in climate projections aggregated at NUTS2 level. In this study we assume that the impact is highly robust when *R* is above 0.8 (Knutti & Sedláček, 2012), meaning that more than 80% of model realizations in the NUTS2 region agree on a positive sign of impact when the reference management scenario is considered.

2.5 Vulnerability to soil degradation

Soil degradation is the decline in soil quality caused by degradation processes such as water and wind erosion, loss of soil organic matter, salinization, acidification, contamination, sealing or compaction. In this study we address impacts of water erosion and adverse changes in soil organic matter and nutrient dynamics, including soil organic matter mineralization, nutrient leaching and loss from export through harvested products, while other degradation processes are not accounted for. More details can be found in Text S3 in the Supporting Information. Yield vulnerability (*Vs*) is quantified as a fraction of projected calorie yield that may be lost due to harmful effects of soil degradation. Business-as-usual fertilization and irrigation determine the capacity to stabilize yields on degraded soils.

The impact of changing soil properties on crop yields was calculated by comparing crop yield impacts simulated with constant soil profile (*con*) relative to the simulations with dynamic soil profile (*dyn*), both in the BAU scenario (Eq 3). The dynamic soil mode allows accounting for changing soil properties under a certain management over time (Basso et al., 2015) and it is used to estimate impacts of climate change in interactions with soil degradation. The coupled soil organic carbon and nitrogen routine (Izaurralde et al., 2006, 2012) that was parameterized for high-input agricultural systems in Central Europe by the authors of this study and the small-watershed Modified Universal Soil Loss Equation erosion method (Williams, 1995) were used herein. Vulnerability to soil degradation (in Gcal ha^{-1}) was calculated for each grid (*p*) and climate change scenario (*s*) by Eq (3).

$$Vs_{p,s} = I(con)_{p,s} - I(dyn)_{p,s} \,, \tag{3}$$

where *I* is 30-year mean yield impact (in Gcal ha^{-1}) of +2° warming relative to the historic period (1971–2000) calculated in the respective soil-handling and climate scenarios. Despite the importance of conservation agriculture for soil protection, conservation practices were not included in our large scale analysis. Possible implications are tested in the uncertainty analysis (Section 2.6.1).

2.6 Evaluation of uncertainties in the modelling approach

To account for the potentially large uncertainty in simulating future climate change impacts with EPIC we performed an extensive uncertainty analysis for the impact estimates presented herein with respect to the dimensions of temperature and CO_2 effects, soil degradation modelling, and management intensification.

2.6.1 Evaluation of uncertainties in modelling temperature, CO_2, and soil degradation effects

We performed a detailed uncertainty analysis (UA) for Belgium, Lithuania, Portugal and Slovakia aiming to quantify uncertainty in yield simulations due to synergic interactions of increased temperature, atmospheric CO_2 and soil degradation effects across (1) different climatic regions with contrasting changes in temperature and precipitation patterns, and (2) regions with different intensity of nutrient inputs.

Since soil input data, tillage practices and parameterization of underlying bio-geochemical processes represent an important source of uncertainty in EPIC (particularly in the *dyn* scenario), we randomized a range of tillage and residue management variables, such as the number and intensity of soil cultivations and crop residue return rates, to account for diversity in cultivation practices. In addition, we assumed that a fraction of BAU N fertilization comes as farmyard manure to account for additional carbon inputs with organic fertilization. Finally, we vary the most sensitive parameters and soil initial values which drive soil organic matter and erosion dynamics in EPIC to address parameterization and input uncertainties. The parameter ranges used in the UA (PARM in Table 3) follow recommendations of EPIC developers (Gerik et al., 2013), while the default values from Table 3 were used in our impact analysis. A detailed description of parameters and variables can be found in Gerik et al. (2013). The subset of parameter values used to imitate soil conservation practices is also summarized in Table 3. The Latin Hypercube method (McKay, 1992) was used to initiate a total of 3000 parameter and variable combinations for each simulated unit. For example, more than 28 million of EPIC simulations were performed for Portugal (3000 parameter combinations × 4790 SimUs × 2 CO_2 scenarios).

The KNMI climate projection (Table 1) was used for the UA, being close to the ensemble median in terms of temperature change rate. All simulations described above were performed with constant (360 ppm) and transient atmospheric CO_2 concentration (from 325 ppm in 1971 up to 700 ppm in 2100). The impact of temperature was analysed by grouping all yield data simulated for the +2°C period into ΔT intervals separated by 0.5 °C steps, where ΔT is relative to the mean annual temperature from 1971 to 2000. A more generic modelling experiment was carried out to provide an extended insight into the uncertainty due to incrementally increasing temperature and CO_2. Two contrasting crops, namely C_3 wheat and C_4 maize, were used for this purpose. More detailed description is in Text S2 in the Supporting Information.

<TABLE 3>

2.6.2 Evaluation of uncertainties due to crop intensification

Crop management scenarios with ample nutrient and water supply (P1 and P2) were evaluated relative to the BAU scenario to bracket projected yield uncertainties related to the range of future intensification levels. The uncertainty range is expressed as a yield difference between the baseline BAU projection and the respective high-input scenarios under +2°C. Crop intensification options other than more intensive irrigation and fertilization are not accounted for herein.

3 Results

3.1 Crop calorie yield at the +2°C threshold

At the national level, a positive calorie yield change was estimated for all EU Member States at the +2°C warming threshold, albeit with different robustness across climate projections and variability at sub-national level. Figure 1 demonstrates yield ranges estimated from the full ensemble of climate projections under the BAU scenario and transient atmospheric CO_2 concentration. Ensemble mean +2°C yield impacts relative to the baseline (1971–2000, BAU), and its 5th to 95th range of yield projections and robustness in the ensemble, are aggregated at sub-national level (NUTS2 regions) in Figure 2. Mean calorie yield changes for individual ensemble members are presented in Table S3 in the Supporting Information.

<FIGURE 1>

The most positive relative impact with robustness above 90% was simulated over Northern Europe, with a lower impact magnitude in the Baltic countries. The aggregated calorie yield is expected to increase by more than 17% (20–34 Gcal ha^{-1}) in Denmark, Ireland, U.K. and Finland, and by 12% (15 Gcal ha^{-1}) in the Baltics. The climate projection-related yield impact uncertainty ranges from +6% to +20% in regions of the Baltic countries, and from +7% to +30% in other regions in the north (Figure 2). Yield changes and impact robustness of individual crops are summarized in Figure S1 and Table S2.

At the national level, an increase by 17–38 Gcal ha^{-1} was estimated for Western European countries, i.e. countries which currently belong to the most productive in Europe. The lowest but still robustly estimated positive impact was ~6% as projected for south-western France (Figure 2). There is a large yield impact range projected in France, ranging from –2% to +40% in the south-western regions. In general, the ranges in yield projections are larger in regions with cooler montane climate. Maize and other summer crop yields except for sugar beet would increase the most, especially in higher altitudes. Owing to its long growing season, sugar beet tends to be negatively though not robustly affected in various parts of Western Europe (Figure S1, Table S2).

In the countries of the Balkan Peninsula, at the national average, a small overall increase of 6 to 13 Gcal ha^{-1} was calculated, while for the other Eastern European countries a moderate gain of 17 to 27 Gcal ha^{-1} was estimated. The climate change impacts are largely uncertain across EURO-CORDEX scenarios and the yield change projections are therefore insufficiently robust in many NUTS2 regions in Romania and Bulgaria (Figure 2). The projected yields range from –10% to +25%, and from –5% to +20% in regions of Bulgaria and Romania, respectively. Despite the positive overall impact demonstrated in Figure 1, all crops experienced a decrease in yields in at least some simulated climate change scenarios in these regions (Figure S1).

Only a small positive impact of less than 8% (2–18 Gcal ha^{-1}) was estimated over the Mediterranean countries when the BAU crop management scenario is considered. The highest calorie increase was projected for Italy and Slovenia, owing to relatively high share of cooler montane regions. Large bars in Figure 1 reveal high yield variability due to heterogeneous site conditions and projected weather variability. A substantial disagreement among climate projections makes the overall yield impact estimates insufficiently robust and largely uncertain in many regions of Portugal, Spain and Greece, where the sub-national calorie yield changes ranged between strongly negative of –20 % and positive of up to 35% (Figure 2).

<FIGURE 2>

3.2 Climate effects on calorie yields

We carried out a detailed analysis to quantify the contribution of elevated CO_2 and projected seasonal temperature and precipitation patterns to the regional calorie yield changes summarized in Section 3.1. Irrigated BAU simulations were used to address irrigated and high-rainfall cropland, while rainfed simulations from the areas dominated by water stress (water stress in >50% days of the growing period) were used to disentangle the impacts of precipitation on water limited production (Figure 3).

Elevated CO_2 and seasonal temperature are two dominant climatic factors determining yield changes in Northern Europe. A robust increase in seasonal temperature sum (10–40%) resulted in calorie yield changes ranging from –8% in Lithuania to +7% in Ireland when CO_2 was fixed at 360 ppm, whilst a consistently positive calorie yield change of +13% to +25% was simulated with elevated CO_2 (circles in Figure 3a). The positive impact is composed of (1) a strong fertilization effect of elevated CO_2 on winter crops, which would be affected rather negatively if CO_2 remained constant (Text S2, also Figure S2 and S10), and (2) more favourable temperature conditions for summer and root crops, allowing them to be more viable on cropland farther north. For example, the mean sunflower yield achieved in Europe around the year 2000 (about 2 t ha^{-1}) would be exceeded on more than 50% of existing cropland, except for the far north areas of Finland (data not shown). Changes in precipitation alone do not affect our yield projections since crops are not critically limited by water deficit. However, >10% increase in rainfall during the long growing seasons affected the yields negatively via reduced solar radiation, leading to the weak response of yields to increased temperature in the north ($r^2 < 0.4$ in most countries in Figure 3a). It is also important to note that detrimental effects of increased precipitation such as hampering field operations or damage due to heavy rains are not addressed in this analysis.

Owing to an increase in seasonal temperature by ~13%, the irrigated and high-rainfall calorie yields would increase by 1–3% and 19–23% with fixed and elevated CO_2, respectively, in Western Europe, but only by 13% in the latter case in France. Importantly, water-limited yields in southern France decreased by 5% when CO_2 effect is not considered. Yet, elevated CO_2 has the potential to offset the negative effects, leading to an overall increase by 4% (Figure 3b). In general, maize and other summer crops would benefit from alleviated low temperature limitations in the wetter and cooler parts of Western Europe, while winter crops and tubers will benefit from elevated CO_2. Winter cereals would be affected negatively without elevated CO_2 fertilization (Text S2, also Figure S2 and S10).

A positive effect of increased temperature under elevated CO_2 was simulated also for irrigated and high-rainfall crops in Eastern Europe ($r^2 > 0.6$ in all countries except for Poland in Figure 3a). A ~13% temperature increase in the growing period, together with elevated CO_2 of up to 470 –580 ppm at +2°C, stimulated the calorie yields by about 17–21% in Czechia, Poland and

Slovakia, and by 9–12% in Hungary, Bulgaria and Romania. The impact is much weaker at fixed CO_2 levels though: from –1% to +4% on the country average, while a positive yield response is in most cases visible only at higher warming rates simulated for the montane climate (Figure 3a). In general, the yield change is dominated by higher productivity of summer crops and tubers under elevated CO_2 (Figure S2). A benefit from CO_2 fertilization could more or less offset the losses in winter cereal yields expected due to shortening of the growing period (Text S2 in the Supporting Information). Water-limited calories production in the driest Pannonian lowlands of Hungary, Bulgaria, and especially Romania, is sensitive to the altered precipitation patterns (Figure 3b). For example, in Romania, a 10% increase in growing season precipitation may lead to 8% gain in crop calories productivity despite the increase in daily rainfall amounts (Figure S12). Dryland areas would also significantly benefit from elevated CO_2, potentially offsetting the yield losses corresponding to a precipitation decrease by ~5% in Bulgaria and Romania dryland. Projected changes in seasonal temperature and precipitation alone resulted in calories change from –6% to +1%, but from +4% to +13% when combined with elevated CO_2 effects (Figure 3b).

In Southern Europe, calories from well-watered crops demonstrate a significant linear relationship with changes in seasonal temperature (Figure 3a). A 10–15% temperature raise stimulated calorie yields by 5–14% when supplemented by an additional 100 to 200 ppm of atmospheric CO_2 compared to the baseline, while the impact was negative to slightly positive (–4% to +2%) under the present-day CO_2. Water-limited calorie yields are significantly sensitive to precipitation changes together with elevated CO_2 in Spain, Italy, Greece and Portugal (Figure 3b, F-test $P < 0.001$ for all regressions). In dryland areas, calorie yields would be impacted mostly negatively at the present-day CO_2 levels. Yet, elevated CO_2 may offset these losses due to fertilization effect on C_3 crops, and increased crop water use efficiency (Figure S2, also Text S2 and Figure S10). The estimates in Figure 3b indicate that elevated CO_2 may potentially offset calorie losses corresponding to a precipitation decrease by ~10% in the Mediterranean dryland.

<FIGURE 3>

3.3 Vulnerability to soil degradation

Eastern and some Northern EU countries will be especially vulnerable if crops continued to be managed with BAU input intensity, since the current inputs don't provide the capacity to overcompensate for future degradation-induced nutrient losses. In Eastern Europe apart from Czechia, the vulnerability ranged between 21 and 32 Gcal ha^{-1} in Romania and Hungary (Figure 4), respectively, while the highest relative loss (>20%) was estimated in parts of Bulgaria, Romania, Hungary and Slovakia (Figure S4). The uncertainty range across individual climate projection is presented in Figure 4. With current fertilization at 40–50% of the intensity needed for crops growing without nutrient stress (Figure S3a), nutrient inputs would not sufficiently compensate for weakening soil fertility under +2°C. An even higher vulnerability of > 40 Gcal ha^{-1} was simulated for the Baltic states with soil carbon loss due to warmer climate (Figure S5) amplifying insufficient nutrient supply under the BAU scenario (fertilization < 40% of the intensity under P1). The fraction of calories in Eastern European and the Baltic countries vulnerable to losses due to soil degradation is in most cases higher than the calorie yield gain due to climate change (Figure 1). Moreover, in Bulgaria and Romania, caloric yield vulnerability is over 40% higher when irrigated systems alone are considered (Figure 4). Therefore, soil degradation may negatively outweigh positive impacts of +2°C when not prevented by adaptation measures. Western European states are generally less vulnerable as they have more capacity to overcompensate soil degradation effects via sufficient fertilizer supply. Current N-fertilization intensities are at 60 to 140% of the quantity required for unstressed plant growth, offsetting harmful effects of nutrient losses on degraded soils. Consequently yield vulnerability only seldom exceeded 10% (Figure S4). In Southern Europe, rainfed systems would be little to moderately susceptible to soil degradation since the yield would be predominantly controlled by water deficit during the growing season (e.g. most of Spain and Greece).

<FIGURE 4>

Due to low level of fertilization, yield vulnerability at +2°C is largely driven by decreasing soil organic matter in the Baltic states and Eastern Europe (Figure S5). For example, simulated carbon stock decreased by 15–20% in the Baltics and by 8–14% in eastern countries when KNMI projection is considered. Country-level median erosion rates calculated from all cropland were below 1 t ha^{-1} in all EU states, except for Ireland, Slovenia and Luxembourg, leading to an annual carbon loss ranging between 6 kg ha^{-1} in Denmark and 120 kg ha^{-1} in Slovenia (Table S6). Losses of more than 100 t ha^{-1} in extreme years were simulated especially in the Mediterranean countries (see 99th percentiles in Table S6). However, erosion contributed only little to the national yield vulnerability under +2°C. As demonstrated in Figure S6, turning off water erosion in the scenario with dynamic soil profile resulted in calorie yield impacts similar to the BAU-*dyn* scenario in Figure 4, since sever erosion affected only a relatively small fraction of the production area. Soils affected by severe erosion of more than 20 t ha^{-1} a^{-1} in more than 5% of croplands were simulated especially in the Mediterranean region (Table S6).

3.4 Uncertainty due to modelling temperature, CO_2, and soil degradation responses

A considerable range of yields was estimated by the UA, while our BAU-*con* and BAU-*dyn* simulations (mean values in green and blue colour, respectively) are located roughly in the mid-range of the respective soil handling scenarios (*con* and *dyn* in red and grey colours, respectively). Figure 5a demonstrates yield uncertainty induced by 1) varied model parameters and inputs, 2) atmospheric CO_2 effect, and 3) spatial heterogeneity in natural conditions since all grids are plotted here.

A decrease in crop calories simulated for Lithuania in Section 3.3 is robust across the whole range of UA-*dyn*. The mean country-level yield declined between –30 and –65 Gcal ha^{-1} relative to the historic period. This is mainly due to decreasing root and winter crop productivity under the degradation *dyn* scenario, while summer crops were positively impacted (Figure S7). A similar though more uncertain effect of +10 to –60 Gcal ha^{-1} was estimated for Slovakia, owing to very heterogeneous terrain and soils. Uncertainty in soil degradation vulnerability, which is the difference between UA-*con* and UA-*dyn* in the +2°C period relative to the respective historic period, is substantial for all analysed countries, but the UA-mean values are in a good agreement with the BAU projections used in Section 3.3 (green and blue lines in Figure 5a).

Importantly, at the scale of our study, avoiding conservation practices from the soil degradation scenario used in the vulnerability analysis (Section 3.3) does not undermine conclusions driven for the +2°C period as the differences between BAU-*dyn* and conservation UA-*dyn* scenarios are marginal there (Figure 5a, "Till effect" panel). In general, historical yields under emulated conservation practices are on average 85 to 95% of conventional yields, and in Belgium it remains similar also in the future. The relative loss is higher in cooler regions of Lithuania and parts of Slovakia, whilst almost equal though less variable calorie yields are estimated in Portugal. Yields in the conventional scenario (blue line) decline faster compared to the conservation scenario (purple line) in Slovakia and Lithuania, suggesting that soil conservation slows down the decline in yields by mitigating soil degradation effects.

In the *con* scenario, elevated CO_2 stimulated calories by 40 Gcal ha^{-1} in Belgium, where crops largely benefit from direct CO_2 effect due to ample fertilization and high precipitation. This is not the case in Slovakia, Portugal and Lithuania though, where simulated yields are to a great extent limited by nutrient or water deficiency, and CO_2-induced yield gain is lower (~20 Gcal ha^{-1}) under no degradation, and there is no effect in the degradation scenario (Figure 5a, "CO_2 effect" panel). With atmospheric CO_2 fixed at 360 ppm, rising temperature would have a negative effect on simulated mean calorie yield in all analysed countries except for a small stimulus of mild warming up to 1.5°C in Slovakia (dashed boxes in Figure 5b). The temperature-related impact uncertainty is considerably large due to site heterogeneity, particularly in Portugal and Slovakia: from –80 to +50 Gcal ha^{-1} and –45 to +35 Gcal ha^{-1}, respectively, when +2°C of regional warming is considered. Elevated CO_2 (490 to 605 ppm in the +2°C period) significantly increased calorie yields in all countries and warming intervals (ΔT) compared to constant CO_2 scenario (paired *t*-test P<0.001). Importantly, the growth increment due to CO_2 elevated by ~200 ppm offset temperature increase of +2°C in Belgium, Lithuania and Portugal, and even a higher warming in Slovakia (Figure 5b). The cooler regions in higher altitudes demonstrate larger yield increases along the temperature gradient (data not shown), contributing largely to the overall yield uncertainty in Figure 5b.

In summary, elevated CO_2 overcompensated the negative impacts of local +2°C warming across the whole range of UA in Lithuania and to a lesser extent in other analysed countries under the no-degradation scenario (C+CO_2 versus C–CO_2 in Figure 5c). Soil degradation (D+CO_2) robustly decreased the CO_2-induced yield gain in Belgium, or even reverse the impact sign in most cases in Lithuania, Slovakia and Portugal. Unlike in Belgium, the contribution of elevated CO_2 is only marginal under the degradation scenario in Lithuania, Slovakia and Portugal where yields are dominated by nutrient limitations, and CO_2 cannot compensate for the combined effect of warming and degradation (D+CO_2 and D–CO_2 in Figure 5c). In the degradation scenario, conservation practices (Dc in Figure 5c) reduced the country-mean yield losses, especially in Lithuania, and reduced UA ranges in all analysed countries under both CO_2 scenarios.

<FIGURE 5>

3.5 Bracketing crop intensification uncertainties

Extrapolation of BAU crop fertilization and irrigation management towards the time period of the +2°C threshold represents a considerable source of uncertainty. In this analysis, we used the calorie yields theoretically achievable in high-input agricultural systems under scenarios P1 and P2 to bracket this uncertainty. Mean ranges between the BAU projections and the respective high-input system yields are summarized in Table 4. In general, the yield differences between high-input scenario P1 and BAU are about two (e.g. Belgium and Netherlands) to fifty (Portugal) times higher than the projected climate impacts presented in Section 3.1, indicating that crop intensification has the potential to greatly boost the benefits from climate change in most of

Europe as well as outweigh possible negative effect in the south (not taking into account resource constraints).

<TABLE 4>

The production uncertainty ranges between 30 and 85 Gcal ha^{-1} in most of Northern and Western European countries, with the largest relative values in the Baltics. Particularly large ranges were estimated in France due to irrigation intensification (P1) and expansion (P2) adaptations: almost 60% in the latter scenario. However, compensation for water stress in order to approach the P1 productivity on currently irrigated cropland would require about 100 mm (10–200 mm) of net irrigation annually when averaged across all winter and spring crops (except for rice), which is about two times more than water demand simulated for the present days under BAU management (Figure S8b).

A considerable uncertainty along the crop intensification gradient is estimated also in Eastern Europe: 47–78 Gcal ha^{-1} and 70–182 Gcal ha^{-1} for scenarios P1 and P2, respectively. Approaching the P1 and P2 yields would require a substantial increase in fertilizer inputs particularly in Romania, Bulgaria and Hungary compared to today (Figure S8a). In addition, future irrigation capacity contributes significantly to the overall uncertainty in the Pannonian basin. A much smaller yield difference between BAU and P1 (60–80 Gcal ha^{-1}) compared to P2 (130–180 Gcal ha^{-1}) points to a large uncertainty due to possible expansion of irrigated cropland. However, high net irrigation water requirement of 140–200 mm a^{-1} crop^{-1} on average, and more than 250 mm a^{-1} $crop^{-1}$ in some regions (Figure S8b) would render irrigation expansion challenging.

Possible expansion and intensification of irrigated cropland represents a large projection uncertainty also in Southern Europe, mainly in Spain, Greece, Portugal and Italy. Many regions demonstrate only a limited response to management intensification if currently irrigated cropland is not expanded under P1: 60 Gcal ha^{-1} in Spain and Greece, and about 80–100 Gcal ha^{-1} in Italy, Portugal and Slovenia. With expansion of irrigated cropland under P2 though, the calorie production under +2°C may exceed 300 Gcal ha^{-1}, corresponding to a substantial production uncertainty of more than 200 Gcal ha^{-1} in many regions (Table 4). However, approaching this hypothetical productivity would mean a net irrigation requirement of more than 250 mm a^{-1} $crop^{-1}$ (160 mm in Italy and 60 mm in Slovenia) on almost all available cropland (Figure S8b).

4 Discussion

Business-as-usual crop management with transient CO_2 effects and without soil degradation are standard assumptions in large-scale crop yield impact projections (Elliott et al., 2014; Müller et al., 2015; Rosenzweig et al., 2014). In summary, our BAU-*con* simulations with transient atmospheric CO_2 agree with general expectations of:

(1) a positive effect of warming and elevated CO_2 in Northern Europe and expansion of summer crops on existing cropland further north (cf. Audsley et al., 2006; Eckersten et al., 2001; Hildén et al., 2005; Knox et al., 2016; Olesen et al., 2007; Tuck et al., 2006),

(2) CO_2-induced growth stimulus offsetting a decline in crop productivity (especially cereals) due to shortened growing periods for most of Europe (cf. Asseng et al., 2015; Lobell & Field, 2007; Supit et al., 2010), and

(3) spatially variable and insufficiently robust impacts in Southern and South-Eastern Europe, with a productivity decrease in the most southern and driest areas but an increase in cooler regions (cf. Audsley et al., 2006; Giannakopoulos et al., 2005; Müller et al., 2015; Olesen et al., 2007; Santos et al., 2002).

However, many important aspects of future crop production may remain unnoticed with these "standard" projections, including soil degradation (Louwagie et al., 2011) or future advances in agriculture (Ewert et al., 2005), which we have addressed herein. There are also other caveats concerning the reliability of large-scale assessments such as ours, which are discussed in the following sections.

4.1 Temperature and elevated CO_2 effect

Our simulations suggest that direct fertilization effect of rising CO_2 has the potential to overcompensate negative effects of increased temperature in irrigated and high-rainfall systems as well as in some water-limited systems in EU (Section 3.2). The overcompensation is sufficiently robust across the whole range of uncertainty analysis for high-input systems in Western Europe (Belgium), but it can be undermined by synergic interactions of soil degradation and insufficient fertilization (e.g. Lithuania in Section 3.4). The reliability of our projections thus critically depends on EPIC's ability to simulate crop yields response to increased temperature and elevated CO_2. Long et al. (2006) raised concern that biophysical models including EPIC may overestimate (by ~50%) the direct CO_2 fertilization effects, which was later disputed (Ewert et al., 2007; Kimball, 2016; Tubiello et al., 2007). Figure S10 in the Supporting Information demonstrates, in a generic way, how the most important crops (C_3 wheat and C_4 maize) respond to temperature increase and elevated CO_2 in our pan-EU EPIC, allowing comparison to published outcomes. In summary, our results agree fairly well with temperature and elevated CO_2 effects experienced in field experiments and field-scale modelling:

(1) A negative response of wheat yields to increasing temperature at the current atmospheric CO_2 concentration in most European environments simulated by EPIC is in a good agreement with results obtained from 30 different wheat field models described by Asseng et al. (2015), and such response has also been evidenced in field experiments (Ottman et al., 2012). A positive effect on rainfed yields in arid conditions (Southern Europe in Figure S10), where accelerated crop growth may prevent plant water and temperature stress later in the season, was also documented by Asseng et al. (2013).

(2) A 10–20% yield gain stimulated by +200 ppm of CO_2 at present temperature as simulated by EPIC (+0°C bin in Figure S10a,b) is in accordance with wheat experimental data (Ainsworth & Long, 2004; Kimball, 2016; O'Leary et al., 2015). Roughly similar average gains under +200 ppm of CO_2 were also reported for other C_3 crops, including rice and barley, soy bean, potatoes and sugar beet by Kimball (2016).

(3) A higher response to elevated CO_2 under rainfed compared to irrigated conditions can be attributed to improved water use-efficiency as has been reported also from field experiments (e.g. Kimball, 2016). A combined effect of CO_2 fertilization and reduced transpiration may partly off-set negative impacts on C_3 crops in dry regions, although the full advantage from elevated CO_2 can only be realized when irrigated (e.g. Dono et al., 2016).

(4) In accordance with the under-laying experimental data used to parameterize EPIC (Kimball, 1983), simulated maize yields demonstrate ~10% increase due to CO_2 concentration elevated from 360 to 550 ppm in both rainfed and irrigated conditions. However, recent analyses indicate that maize may have only marginal or no yield response to elevated CO_2 under ample water supply, while more substantial response of about 18% has been reported for water-limited environments (Kimball, 2016). This overestimation in maize response to elevated CO_2 may contribute to cancelling out the negative effects of warming, especially in Southern Europe (Figure S10c,d).

4.2 Soil degradation concept

Future soil degradation and its impacts on crop production is unknown and uncertain by nature since it will depend on intensity of hazardous processes, exposure, vulnerability, and cropland management. In this study we quantify vulnerability (Oppenheimer et al., 2014) as a “predisposition” of calorie yields to be adversely affected by soil degradation. From a variety of degradation processes (e.g. Louwagie et al., 2011) we address the decline in fertility due to nutrient and soil organic matter depletion and soil erosion. Other degradation processes, such as soil structure decline, salinization or acidification, are not represented here (see also Text S3). As expected, fertilization is the dominant factor controlling yield vulnerability in this study since it determines the capacity to offset the degradation-induced nutrient losses. Fertilization intensity, which is a fraction of BAU fertilization over fertilization needed for crop yields without nutrient stress (scenario P1), explains more than 50% of variability in the *Vs* values (Figure S3a). On the contrary, irrigation intensity has only a small effect on yield vulnerability (Figure S3b), suggesting that the soil’s ability to supply water is affected less at our scale of analysis. Changes in hydro-physical soil properties (wilting point and field water capacity) as simulated by pan-EU EPIC are of inferior importance compared to the changes in soil organic matter pool (Figure S11). More detailed description and discussion with this respect is provided in Text S3 in the Supporting Information. It should be noted that our concept does not account for processes of organic carbon and nutrient redistribution, which contribute additional uncertainty on soil vulnerability (e.g. Paustian et al., 2016).

Intensive fertilization may indeed overcome limitations due to soil degradation by SOC loss so that crop yields are not affected (Holland, 2004), but it may also lead to environmental pollution (Sutton, 2011) and adverse trends in soil health hampering future production (Squire et al., 2015). Therefore, soil conservation has been recognized as a prominent adaptation strategy when coping with soil degradation (Bindraban et al., 2012; Montanarella, 2015). Given the diversity of practices in conservation agriculture and a lack of consolidated data in Europe (e.g. Merante et al., 2017), conservation practices are not explicitly included in out vulnerability assessment in Section 3.3. We examine possible implications of avoiding conservation practices for our analysis in Section 3.4 by analysing the calorie yields simulated under assumptions of 1) low intensity of soil disturbance, 2) high crop residue return, 3) mulching, 4) manure fertilization, 5) and high erosion control (see Table 3), i.e. measures known to enhance soil quality (Lal, 2004). First, the effects of conservation practices generated by pan-EU EPIC are in general accordance with expectations: our historical yields under conservation practices are on average 85 to 95% of conventional yields (de Ponti et al., 2012; Soane et al., 2012), and the relative loss is higher in cooler regions (Lithuania), whilst almost equal though less variable calorie yields are estimated in Portugal. Indeed, conservation practices are particularly appropriate in semi-arid regions where they allow for better water management and erosion control (Pittelkow et al., 2015; Soane et al., 2012). Second, avoiding conservation practices does not undermine the robustness of our vulnerability analysis (see Section 3.3).

Many studies identified water erosion among major soil threats with a negative impact on crop production, both in terms of affected area and impact intensity (Holland, 2004; Panagos et al., 2015). However, given the scale and design of our study, erosion contributed only little to the national calorie yield vulnerability. With ~3.5 t ha^{-1} we slightly underestimated the average annual erosion rate in EU croplands compared to 5 t ha^{-1} estimated by Panagos et al. (2015) when the corresponding time periods are considered. Besides, we estimated that approximately 9% of EU croplands is currently affected by soil loss of more than 5 t ha^{-1} a^{-1} (data not shown), while Panagos et al. (2015) reported ~13%. Therefore, we assume that the soil erosion effects on yields may be underestimated in our study. It is worth noting that only deep soils were considered in this study (see Text S3), which may have contributed to the underestimation of soil loss impacts on crop yields.

4.3 Crop intensification implications

Large yield potentials (scenario P1 and P2, Section 3.5) suggest that possible future intensification of fertilization and irrigation may represent a substantial uncertainty for projected calorie yields at +2°C (Table 4). Looking back, we learn that crop intensification was undoubtedly among main drivers of yield increase in the past. For example, wheat yields in Europe have nearly tripled since 1960 because of intensification and improved crop management (Ewert et al., 2007). However, regardless of the untapped future potential, major changes towards more intensive fertilization are foreseen only by farmers in the northernmost regions and, to a lesser extent, in continental and Pannonia zones (Olesen et al., 2011). In fact, more intensive fertilization is not a policy option for Central and Western European croplands because of serious pollution of ground and surface waters in many watersheds and aquifers. Besides, assuming that a maximum ~80% of the yield potential can be utilized by farmers (van Ittersum et al., 2013; Lobell et al., 2009), the BAU fertilization already provides sufficient supply to capitalize from +2°C in most of Western and Northern Europe, except for the Baltics. Improved fertilizer use efficiency in particular of organic fertilizers together with other technological developments and breeding are likely options in those high-intensity regions in order to comply with the EU environmental policies (Levers et al., 2016). In Eastern and South-Eastern Europe, though, increased fertilizer application is likely required to take the advantage of the +2°C warming. Increasing trends in fertilizer application rates are already reality in some countries, such as Czechia or Poland (Levers et al., 2016; Sutton, 2011). Future development will strongly depend on economic and political boundary conditions, including agricultural and environmental policies in the EU.

Irrigation availability will doubtlessly determine future yields in dry zones of Southern and Pannonian Europe (Section 3.5). Expansion of irrigation on rainfed cropland under scenario P2 and intensification of the existing irrigation systems under scenario P1 bracket large projection uncertainties in these regions (Table 4). However, even when targeting at 80% of the potential productivity, the net irrigation requirement would about double on currently irrigated cropland compared to today, and approximately the same quantity would be needed on vast areas of currently rainfed cropland in case of irrigation expansion (Figure S8b). Out of the options evaluated here, water availability will therefore be the key factor for future intensification. Probably due to concerns about future water scarcity (Elliott et al., 2014; Lehner et al., 2006) large irrigation expansion for food crops is not expected by farmers in very dry zones (Olesen et al., 2011).

Besides intensification of nutrient and water managements, other adaptation options, policies and market-driven changes represent additional drivers and uncertainties of future calorie yields that are not addressed in this study.

4.4 General limitations of the modelling approach

Despite efforts to quantify and bracket uncertainties, limitations remain in our large-scale study especially with respect to insufficiently captured heterogeneity in crop management practices, including distribution of crop varieties, cultivation practices, fertilization and irrigation allocation to individual crops (Balkovič et al., 2013, 2014; Wriedt et al., 2009), under-performing calibration with respect to climate change (Xiong et al., 2016), insufficiently captured soil heterogeneity (Folberth, Skalský, et al., 2016), uncertainty of crop yield aggregations (Porwollik et al., 2016), and may lack relevance at small scales (van Ittersum et al., 2013).

There are also limits concerning the bio-physical models' ability to represent extreme weather events. Increased frequency and intensity of extreme heat, drought or heavy rains will doubtlessly undermine future yield production. For example, heat can cause water stress by increased atmospheric water demand and depletion of soil water as well as it can directly damage plant tissues, impair flowering, trigger oxidative stress or lower net photosynthesis rates

(Schauberger et al., 2017). Lacking representation of heat shocks in bio-physical crop models could lead to an overestimation of positive impacts. More intensive rainfall (Figure S12) can also hamper future yields. For the +2°C of global warming, Vautard et al. (2014) projected a robust increase in heavy precipitation events everywhere except Southern Europe in summer, with amplitudes in the range 0–20%. However, EPIC, as other crop models, fails to capture the negative impacts of heavy rain and extremely wet conditions. Long-term impacts presented in this study should be less sensitive to such models' deficiencies with respect to the extreme weather events though.

Although elevated CO_2 increases the total protein content in crop yield, it reduces its concentration and thus negatively affects nutritional value of food (Haddad et al., 2016; Myers et al., 2014; Wieser et al., 2008). This aspect is not accounted for in our analysis, but should be kept in mind.

Currently, the use of multiple crop models has become the norm to characterize the uncertainty in climate impacts on crops (Asseng et al., 2015; Müller et al., 2016; Rosenzweig et al., 2014). At the same time though, the wide range and limited comparability of regional outputs, even among models with similar biophysical algorithms, raise some concern (Folberth, Elliott, et al., 2016). Given the limitations on both sides, the skills of pan-European EPIC against the multi-model approach should be explored.

5 Conclusions

Assuming current crop management practices and increasing CO_2 concentrations, a robustly positive calorie yield change of 5 to 20% under future +2°C scenarios was simulated for the EU except for some NUTS2 regions in Bulgaria, Romania, Portugal, Spain, Greece and Italy (Figure 2). Owing to inherent uncertainty in EURO-CORDEX projections, the impact results are largely uncertain in these regions (form –10% up to 30% at 5th to 95th percentiles), and they are well below the acceptable threshold for robustness.

The positive impact is mostly stimulated by 1) CO_2 fertilization effect, and 2) improved growing season temperatures for summer crops in Northern Europe and in higher altitudes. The projections suggest that 100 to 200 ppm more CO_2 in the atmosphere under +2°C compared to the baseline will overcompensate otherwise mostly negative, or only a slightly positive, effects of warming in temperature limited (high-rainfall and irrigated) systems as well as in some water-limited environments in Europe (Figure 3). There are some caveats concerning the fertilization effect of elevated CO_2. For example, the impacts on temperature-limited systems would be considerably smaller, but still mostly positive, when only ~50% efficiency of CO_2 fertilization is considered (roughly halfway between the circles in Figure 3a): about 10% or less in most countries of Western, Northern and Eastern Europe. The impacts on water-limited systems of Southern and South-Eastern Europe will be even more uncertain, varying between slightly negative and positive. A possible overestimation in maize response to elevated CO_2 in EPIC may contribute to lessening out the negative effects of warming, especially in Southern Europe.

Soil degradation in terms of SOM decrease could be a serious threat for European agriculture under +2°C warming. Potential yield losses of more than 20% in some Eastern European and Baltic regions may undermine the positive impact of elevated CO_2 and warming if soil nitrogen status degradation is not prevented. At a country level, soil erosion contributed only little to the calorie yield vulnerability since severe erosion affected only a small fraction of cropland area. Nutrient status is more undermined by organic matter mineralization, nutrient leaching and loss from nitrogen export through harvested products. Agricultural systems with currently insufficient fertilization are especially vulnerable since they don't have the capacity to 1) overcompensate for losses due to nutrient depletion, and 2) benefit from rising CO_2 and warming. In contrast, fertilization surplus in some Western European countries provides sufficient capacity to cope with soil degradation. It should be noted that in spite of the robust response to fertilization intensity (Figure S3a), the vulnerability analysis is burdened by a considerable uncertainty due to modelling of soil processes and crop management practices as quantified in Section 3.4. Nevertheless, this study is a pioneering attempt to address yield vulnerability to future soil degradation.

The highest uncertainty range is related to future intensification options. The uncertainty bracketed by scenarios P1 and P2 is about two to fifty times higher than the projected impacts due to climatic changes. More intensive fertilization and irrigation provide the potential to overcompensate the synergic effects of warming and soil degradation, while still increasing the calorie yield significantly.

Acknowledgments

J.B., R.S., C.F., N.K. and M.O. acknowledge support from EU FP7 project IMPACT2C (grant no. 282746) and the European Research Council Synergy grant IMBALANCE-P (grant no. ERC-2013-SynG-610028). M.M acknowledges support from the Ministry of Agriculture of the Czech Republic (projects no. RO0416 and QJ1610547). Model input data were obtained from sources listed in Table 1. Crop management data needed to reproduce our simulations and data underlying the figures are available at http://pure.iiasa.ac.at/15104/ (DOI: 10.22022/ESM/02-2018.15104). We used the EPIC v.0810 model version available from https://epicapex.tamu.edu.

References

Ainsworth, E. A., & Long, S. P. (2004). What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2: Tansley review. *New Phytologist*, *165*(2), 351–372. https://doi.org/10.1111/j.1469-8137.2004.01224.x

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., … Wolf, J. (2013). Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*. https://doi.org/10.1038/nclimate1916

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., … Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*(2), 143–147. https://doi.org/10.1038/nclimate2470

Audsley, E., Pearn, K. R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M. D. A., … Alexandrov, V. (2006). What can scenario modelling tell us about future European scale agricultural land use, and what not? *Environmental Science & Policy*, *9*(2), 148–162. https://doi.org/10.1016/j.envsci.2005.11.008

Balkovič, J., van der Velde, M., Skalský, R., Xiong, W., Folberth, C., Khabarov, N., … Obersteiner, M. (2014). Global wheat production potentials and management flexibility under the representative concentration pathways. *Global and Planetary Change*, *122*, 107–121. https://doi.org/10.1016/j.gloplacha.2014.08.010

Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., … Xiong, W. (2013). Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. *Agricultural Systems*, *120*, 61–75. https://doi.org/10.1016/j.agsy.2013.05.008

Basso, B., Hyndman, D. W., Kendall, A. D., Grace, P. R., & Robertson, G. P. (2015). Can Impacts of Climate Change and Agricultural Adaptation Strategies Be Accurately Quantified if Crop Models Are Annually Re-Initialized? *PLOS ONE*, *10*(6), e0127333. https://doi.org/10.1371/journal.pone.0127333

Bindraban, P. S., van der Velde, M., Ye, L., van den Berg, M., Materechera, S., Kiba, D. I., … van Lynden, G. (2012). Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability*, *4*(5), 478–488. https://doi.org/10.1016/j.cosust.2012.09.015

Challinor, A. J., Ewert, F., Arnold, S., Simelton, E., & Fraser, E. (2009). Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany*, *60*(10), 2775–2789. https://doi.org/10.1093/jxb/erp062

Dono, G., Cortignani, R., Dell'Unto, D., Deligios, P., Doro, L., Lacetera, N., … Roggero, P. P. (2016). Winners and losers from climate change in agriculture: Insights from a case study in the Mediterranean basin. *Agricultural Systems*, *147*, 65–75. https://doi.org/10.1016/j.agsy.2016.05.013

Eckersten, H., Blombäck, K., Kätterer, T., & Nyman, P. (2001). Modelling C, N, water and heat dynamics in winter wheat under climate change in southern Sweden. *Agriculture, Ecosystems & Environment*, *86*(3), 221–235. https://doi.org/10.1016/S0167-8809(00)00284-X

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., … Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3239–3244. https://doi.org/10.1073/pnas.1222474110

Ewert, F., Rounsevell, M. D. A., Reginster, I., Metzger, M. J., & Leemans, R. (2005). Future scenarios of European agricultural land use. *Agriculture, Ecosystems & Environment*, *107*(2–3), 101–116. https://doi.org/10.1016/j.agee.2004.12.003

Ewert, F., Porter, J. R., Rounsevell;, M. D. A., Long, S. P., Ainsworth, E. A., Leakey, A. D. B., … Schimel, D. (2007). Crop Models, CO2, and Climate Change. *Science*, *315*(5811), 459c–460c. https://doi.org/10.1126/science.315.5811.459c

Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L. B., Obersteiner, M., & van der Velde, M. (2016). Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. *Nature Communications*, *7*, 11872. https://doi.org/10.1038/ncomms11872

Folberth, C., Elliott, J., Müller, C., Balkovic, J., Chryssanthacopoulos, J., Izaurralde, R. C., … Wang, X. (2016). Uncertainties in global crop model frameworks: effects of cultivar distribution, crop management and soil handling on crop yield estimates. *Biogeosciences Discussions*, 1–30. https://doi.org/10.5194/bg-2016-527

Gerik, T., Williams, J., Francis, L., Greiner, J., Magre, M., Meinardus, A., … Taylor, R. (2013). Environmental Policy Integrated Climate Model. User's manual version 0810. Retrieved from http://epicapex.tamu.edu/epic

Giannakopoulos, C., Bindi, M., Moriondo, M., LeSager, P., & Tin, T. (2005). Climate Change Impacts in the Mediterranean Resulting from a 2°C Global Temperature Rise. WWF report, Gland Switzerland.

Haddad, L., Hawkes, C., Webb, P., Thomas, S., Beddington, J., Waage, J., & Flynn, D. (2016). A new global research agenda for food. *Nature*, *540*(7631), 30–32. https://doi.org/10.1038/540030a

Hildén, M., Lehtonen, H., Bärlund, I., Hakala, K., Kaukoranta, T., & Tattari, S. (2005). The practice and process of adaptation in Finnish agriculture. FINADAPT Working Paper 5. Helsinki, Finnish Environment Institute Mimeographs,.

Holland, J. M. (2004). The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture, Ecosystems & Environment*, *103*(1), 1–25. https://doi.org/10.1016/j.agee.2003.12.018

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Izaurralde, R. C., Williams, J. R., McGill, W. B., Rosenberg, N. J., & Jakas, M. C. Q. (2006). Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecological Modelling*, *192*(3–4), 362–384. https://doi.org/10.1016/j.ecolmodel.2005.07.010

Izaurralde, R. C., McGill, W. B., & Williams, J. R. (2012). Development and Application of the EPIC Model for Carbon Cycle, Greenhouse Gas Mitigation, and Biofuel Studies. In *Managing Agricultural Greenhouse Gases* (pp. 293–308). Elsevier. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/B9780123868978000176

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., … Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jaggard, K. W., Qi, A., & Ober, E. S. (2010). Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2835–2851. https://doi.org/10.1098/rstb.2010.0153

Kimball, B. A. (1983). Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 430 Prior Observations1. *Agronomy Journal*, *75*(5), 779. https://doi.org/10.2134/agronj1983.00021962007500050014x

Kimball, Bruce A. (2016). Crop responses to elevated CO2 and interactions with H2O, N, and temperature. *Current Opinion in Plant Biology*, *31*, 36–43. https://doi.org/10.1016/j.pbi.2016.03.006

Knox, J., Daccache, A., Hess, T., & Haro, D. (2016). Meta-analysis of climate impacts and uncertainty on crop yields in Europe. *Environmental Research Letters*, *11*(11), 113004. https://doi.org/10.1088/1748-9326/11/11/113004

Knutti, R., & Sedláček, J. (2012). Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, *3*(4), 369–373. https://doi.org/10.1038/nclimate1716

Köble, R. (2014). *The Global Nitrous Oxide Calculator – GNOC – Online Tool Manual*. European Union. Retrieved from http://gnoc.jrc.ec.europa.eu/documentation/The_Global_Nitrous_Oxide_Calculator_User_Manual_version_1_2_4.pdf

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2008). Soil carbon stocks under present and future climate with specific reference to European ecoregions. *Nutrient Cycling in Agroecosystems*, *81*(2), 113–127. https://doi.org/10.1007/s10705-007-9147-x

Lal, R., Follett, R. F., Stewart, B. A., & Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, *172*(12), 943–956. https://doi.org/10.1097/ss.0b013e31815cc498

Leakey, A. D. B., Ainsworth, E. A., Bernacchi, C. J., Rogers, A., Long, S. P., & Ort, D. R. (2009). Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, *60*(10), 2859–2876. https://doi.org/10.1093/jxb/erp096

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., & Kaspar, F. (2006). Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. *Climatic Change*, *75*(3), 273–299. https://doi.org/10.1007/s10584-006-6338-4

Levers, C., Butsic, V., Verburg, P. H., Müller, D., & Kuemmerle, T. (2016). Drivers of changes in agricultural intensity in Europe. *Land Use Policy*, *58*, 380–393. https://doi.org/10.1016/j.landusepol.2016.08.013

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, *2*(1), 014002. https://doi.org/10.1088/1748-9326/2/1/014002

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources*, *34*(1), 179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Long, S. P., Ainsworth, E. A., Leakey, A. D. B., Nösberger, J., & Ort, D. R. (2006). Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations. *Science*, *312*(5782), 1918–1921. https://doi.org/10.1126/science.1114722

Louwagie, G., Gay, S. H., Sammeth, F., & Ratinger, T. (2011). The potential of European Union policies to address soil degradation in agriculture. *Land Degradation & Development*, *22*(1), 5–17. https://doi.org/10.1002/ldr.1028

Lugato, E., Panagos, P., Bampa, F., Jones, A., & Montanarella, L. (2014). A new baseline of organic carbon stock in European agricultural soils using a modelling approach. *Global Change Biology*, *20*(1), 313–326. https://doi.org/10.1111/gcb.12292

McKay, M. D. (1992). Latin hypercube sampling as a tool in uncertainty analysis of computer models (pp. 557–564). ACM Press. https://doi.org/10.1145/167293.167637

Meersmans, J., Arrouays, D., Van Rompaey, A. J. J., Pagé, C., De Baets, S., & Quine, T. A. (2016). Future C loss in mid-latitude mineral soils: climate change exceeds land use mitigation potential in France. *Scientific Reports*, *6*, 35798. https://doi.org/10.1038/srep35798

Merante, P., Dibari, C., Ferrise, R., Sánchez, B., Iglesias, A., Lesschen, J. P., … Bindi, M. (2017). Adopting soil organic carbon management practices in soils of varying quality: Implications and perspectives in Europe. *Soil and Tillage Research*, *165*, 95–106. https://doi.org/10.1016/j.still.2016.08.001

Montanarella, L. (2015). Agricultural policy: Govern our soils. *Nature*, *528*(7580), 32–33. https://doi.org/10.1038/528032a

Monteith, J. L. (1977). Climate and the Efficiency of Crop Production in Britain. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *281*(980), 277–294. https://doi.org/10.2307/2417832

Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T. A. M., & Schmid, E. (2015). Implications of climate mitigation for future agricultural production. *Environmental Research Letters*, *10*(12), 125004. https://doi.org/10.1088/1748-9326/10/12/125004

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovic, J., Ciais, P., … Yang, H. (2016). Global Gridded Crop Model evaluation: benchmarking, skills, deficiencies and

implications. *Geoscientific Model Development Discussions*, 1–39. https://doi.org/10.5194/gmd-2016-207
Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D. B., Bloom, A. J., … Usui, Y. (2014). Increasing CO2 threatens human nutrition. *Nature*, *510*(7503), 139–142. https://doi.org/10.1038/nature13179
O'Leary, G. J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C., … Asseng, S. (2015). Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology*, *21*(7), 2670–2686. https://doi.org/10.1111/gcb.12830
Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., … Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, *34*(2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003
Olesen, J. E., Carter, T. R., Díaz-Ambrona, C. H., Fronzek, S., Heidmann, T., Hickler, T., … Sykes, M. T. (2007). Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change*, *81*(S1), 123–143. https://doi.org/10.1007/s10584-006-9216-1
Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., & Takahashi, K. (2014). Emergent risks and key vulnerabilities. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]*. (pp. 1039–1099). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Ottman, M. J., Kimball, B. A., White, J. W., & Wall, G. W. (2012). Wheat Growth Response to Increased Temperature from Varied Planting Dates and Supplemental Infrared Heating. *Agronomy Journal*, *104*(1), 7. https://doi.org/10.2134/agronj2011.0212
Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., … Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, *54*, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012
Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174
Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., van Groenigen, K. J., Lee, J., … van Kessel, C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, *183*, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020
de Ponti, T., Rijk, B., & van Ittersum, M. K. (2012). The crop yield gap between organic and conventional agriculture. *Agricultural Systems*, *108*, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004
Porwollik, V., Müller, C., Elliott, J., Chryssanthacopoulos, J., Iizumi, T., Ray, D. K., … Wu, X. (2016). Spatial and temporal uncertainty of crop yield aggregations. *European Journal of Agronomy*. https://doi.org/10.1016/j.eja.2016.08.006
R Core Team. (2016). A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Muller, C., Arneth, A., … Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, *111*(9), 3268–3273. https://doi.org/10.1073/pnas.1222463110

Santos, F. D., Forbes, K., & Moita, R. (2002). *Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures. SIAM project report.* Gradiva, Lisbon, Portugal.

Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., … Frieler, K. (2017). Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications*, *8*, 13931. https://doi.org/10.1038/ncomms13931

Smith, P., Gregory, P. J., van Vuuren, D., Obersteiner, M., Havlik, P., Rounsevell, M., … Bellarby, J. (2010). Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2941–2957. https://doi.org/10.1098/rstb.2010.0127

Soane, B. D., Ball, B. C., Arvidsson, J., Basch, G., Moreno, F., & Roger-Estrade, J. (2012). No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research*, *118*, 66–87. https://doi.org/10.1016/j.still.2011.10.015

Squire, G. R., Hawes, C., Valentine, T. A., & Young, M. W. (2015). Degradation rate of soil function varies with trajectory of agricultural intensification. *Agriculture, Ecosystems & Environment*, *202*, 160–167. https://doi.org/10.1016/j.agee.2014.12.004

Stockle, C. O., Williams, J. R., Rosenberg, N. J., & Jones, C. A. (1992). A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I—Modification of the EPIC model for climate change analysis. *Agricultural Systems*, *38*(3), 225–238.

Supit, I., van Diepen, C. A., de Wit, A. J. W., Kabat, P., Baruth, B., & Ludwig, F. (2010). Recent changes in the climatic yield potential of various crops in Europe. *Agricultural Systems*, *103*(9), 683–694. https://doi.org/10.1016/j.agsy.2010.08.009

Sutton, M. A. (Ed.). (2011). *The European nitrogen assessment: sources, effects, and policy perspectives*. Cambridge, UK ; New York: Cambridge University Press.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671–677. https://doi.org/10.1038/nature01014

Tubiello, F. N., Soussana, J.-F., & Howden, S. M. (2007). Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19686–19690. https://doi.org/10.1073/pnas.0701728104

Tubiello, Francesco N., Amthor, J. S., Boote, K. J., Donatelli, M., Easterling, W., Fischer, G., … Rosenzweig, C. (2007). Crop response to elevated CO2 and world food supply: A comment on "Food for Thought…" by Long et al., Science 312:1918–1921, 2006. *European Journal of Agronomy*, *26*(3), 215–223. https://doi.org/10.1016/j.eja.2006.10.002

Tuck, G., Glendining, M. J., Smith, P., House, J. I., & Wattenbach, M. (2006). The potential distribution of bioenergy crops in Europe under present and future climate. *Biomass and Bioenergy*, *30*(3), 183–197. https://doi.org/10.1016/j.biombioe.2005.11.019

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., … Jacob, D. (2014). The European climate under a 2 °C global warming. *Environmental Research Letters*, *9*(3), 034006. https://doi.org/10.1088/1748-9326/9/3/034006

Werner, M. (2001). Shuttle Radar Topography Mission (SRTM) Mission Overview. *Frequenz*, *55*(3–4), 75–79. https://doi.org/10.1515/FREQ.2001.55.3-4.75

Wieser, H., Manderscheid, R., Erbs, M., & Weigel, H.-J. (2008). Effects of Elevated Atmospheric CO_2 Concentrations on the Quantitative Protein Composition of Wheat Grain. *Journal of Agricultural and Food Chemistry*, *56*(15), 6531–6535. https://doi.org/10.1021/jf8008603

Williams, J. R. (1995). The EPIC model, in: Singh, V.P. (Ed.), Computer models of watershed hydrology (pp. 909–1000). Water resources publisher, Colorado.

Wösten, J. H. ., Lilly, A., Nemes, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma*, *90*(3–4), 169–185. https://doi.org/10.1016/S0016-7061(98)00132-3

Wriedt, G., van der Velde, M., Aloe, A., & Bouraoui, F. (2009). A European irrigation map for spatially distributed agricultural modelling. *Agricultural Water Management*, *96*(5), 771–789. https://doi.org/10.1016/j.agwat.2008.10.012

Xiong, W., Skalský, R., Porter, C. H., Balkovič, J., Jones, J. W., & Yang, D. (2016). Calibration-induced uncertainty of the EPIC model to estimate climate change impact on global maize yield: CALIBRATION-INDUCED UNCERTAINTY. *Journal of Advances in Modeling Earth Systems*, *8*(3), 1358–1375. https://doi.org/10.1002/2016MS000625

Table 1. List of input data sets included in the gridded pan-European EPIC model

Data set	Description	Spatial resolution	Temporal resolution	Source
Climate change	Bias-corrected data from EURO-CORDEX database, including daily minimum and maximum temperature, shortwave solar radiation, precipitation and relative humidity.	0.11 arc-deg	Daily, all projections from 1971 to 2100	The Quantifying Projected Impacts Under 2°C Warming (IMPACT2C) Project (http://impact2c.hzg.de)
	Projection name (regional/global climate model):		***+2°C interval:***	EURO-CORDEX data:
	CSC-REMO/MPI-ESM-LR (RCP 4.5)		2050–2079	http://www.euro-cordex.net
	SMHI-RCA4/EC-EARTH (RCP 4.5)		2042–2071	
	KNMI-RACMO22E/EC-EARTH (RCP 4.5)		2042–2071	
	SMHI-RCA4/HadGEM2-ES (RCP 4.5)		2023–2052	
	IPSL-WRF331F/IPSL-CM5A-MR (RCP 4.5)		2028–2057	
Terrain	Shuttle Radar Topographic Mission Data (SRTM)	3’’	N/A	Werner (2001)
	Global 30 Arc Second Elevation Data (GTOPO)	30’’	N/A	http://eros.usgs.gov
Soil	European Soil Bureau Database (version 2.0)	1 km	N/A	https://esdac.jrc.ec.europa.eu
	Database of Hydraulic Properties of European Soils	N/A	N/A	Wösten et al. (1999)
	Map of organic carbon content in the topsoil	1 km	N/A	Lugato et al. (2014)
Land cover	Combined CORINE 2000 and PELCOM land cover map	1 km	N/A	Joint Research Centre
Admin. units	Geographic Information System of the European Commission (GISCO)	NUTS2 sub-national regions	N/A	http://ec.europa.eu/eurostat/web/gisco http://ec.europa.eu/eurostat/web/nuts/overview
Watersheds	European River Catchment Database, version 2			www.eea.europa.eu
Management	Crop sowing dates	50 km	around 2000	Balkovič et al. (2013)
	Regional N and P	NUTS2	around	Balkovič et al. (2013)

	fertilization rates (mineral + organic)	regions	2000	
	Statistics on crop yields	NUTS2 regions	1996-2007	EUROSTAT
	European Irrigation Map (EIM)	1 ha	around 2000	Wriedt et al. (2009)

Table 2. Fertilization and irrigation scenarios to simulate different levels of crop calorie yields

Scenario	**Irrigated cropland area**	**Max. irrigation volume per crop (mm a^{-1})**		**N per crop (kg ha^{-1} a^{-1})**	**P per crop (kg ha^{-1} a^{-1})**
		Presently rainfed	**Presently irrigated**		
BAU	crop-specific	0	1000*	BAU	BAU
P1	all equipped cropland	0	1000*	Max. 250	Automatic
P2	all cropland	1000*	1000*	Max. 250	Automatic

[*] The upper limit of irrigation water supply (simulated irrigation water volume is less or equals 1000 mm a^{-1})

Table 3 List of EPIC input variables and parameters used in the uncertainty analysis; the default values were used in the impact assessment, while the ranges in brackets were used in the uncertainty analysis

EPIC variable / parameter	**Selected default value and range**	**Values used to imitate soil conservation**
Farm yard manure (% of BAU N fertilizer)	0 (20, 40)	40
Number of tillage operations per crop	1,2,3,4,5*	1,2*
Soil mixing by tillage (fraction)	0.5 (0.1–0.9)	< 0.3
Tillage depth (mm)	150 (10–400)	< 100
Erosion control factor (0-1 fraction)	0.5 (0–0.7)	< 0.2
Initial SOC content scaling factor (multiplier)	1 (0.5–1.5)	(0.5–1.5)
Stable humus fraction (fraction)	0.5 (0.3–0.7)	(0.3–0.7)
Soil strength constraint on root growth (PARM2)	1.2 (1–2)	(1–2)
Soil evaporation coefficient (PARM12)	2 (1.5–2.5)	(1.5–2.5)
Microbial decay rate coefficient (PARM20)	0.8 (0.3–1.5)	(0.3–1.5)
Biological mixing depth (PARM24)	0.3 (0.1–0.5)	(0.1–0.5)
Water stress weighting coefficient (PARM35)	0.5 (0–1)	(0–1)
Slow humus transformation rate (PARM47)	0.000548 (0.0003–0.0009)	(0.0003–0.0009)
Passive humus transformation rate (PARM48)	0.000012 (0.0000072–0.00002)	(0.0000072–0.00002)
Tillage effect on residue decay rate (PARM52)	10 (5–15)	(5–15)

* crop-specific number

Table 4. Mean absolute (in Gcal ha^{-1}) and relative (in %) difference between the BAU calorie yields projections relative to the potential yields achievable in high-input systems (in Gcal ha^{-1}, and % relative to BAU), assuming present-day distribution of rainfed and irrigated cropland (scenario P1), and calorie yields unlimited by water and nutrient stress on all available cropland (scenario P2). All differences are statistically significant (the paired *t*-test $P < 0.001$).

Country		**Scenario P1**		**Scenario P2**	
		Gcal ha^{-1}	**%**	**Gcal ha^{-1}**	**%**
Northern Europe	Denmark	60	28	64	30
	Estonia	62	46	63	47
	Finland	33	26	40	32
	Ireland	57	26	62	28
	Lithuania	61	44	67	49
	Latvia	73	52	76	54
	Sweden	56	40	62	44
	U.K.	66	33	83	41
Western Europe	Austria	52	28	82	44
	Belgium	51	23	64	29
	Germany	41	21	64	32
	France	73	34	127	59
	Luxembourg	44	22	68	34
	Netherlands	44	18	60	25
Eastern Europe	Bulgaria	62	47	182	138
	Czechia	47	26	83	46
	Hungary	78	47	131	79
	Poland	58	32	70	38
	Romania	65	44	144	96
	Slovakia	73	46	103	65
Southern Europe	Spain	60	49	244	199
	Greece	55	49	216	192
	Italy	98	58	196	117
	Portugal	99	73	238	174
	Slovenia	76	38	84	42

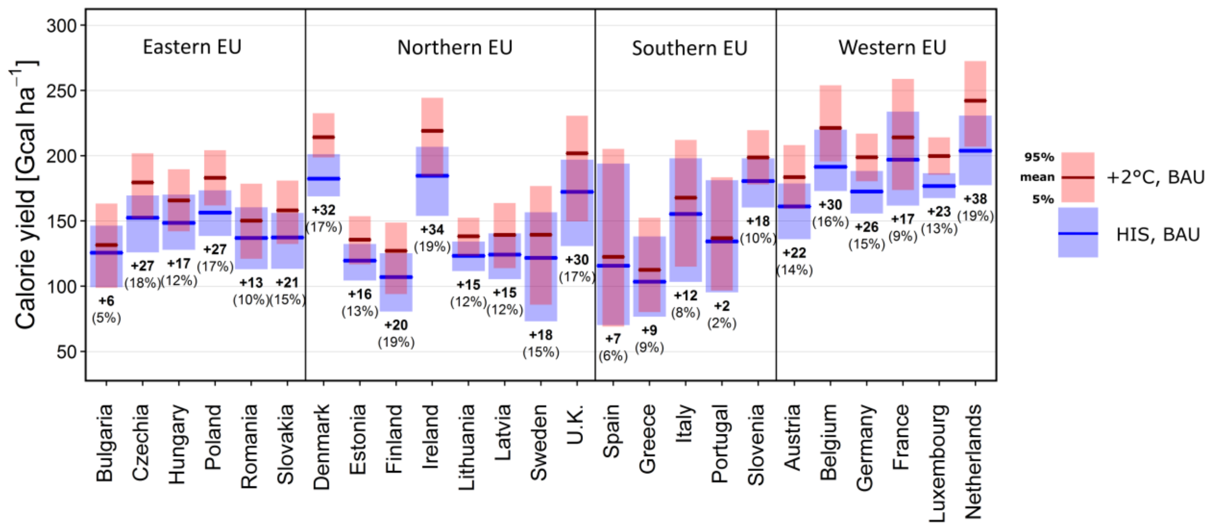
Figure 1 Crop calorie yield (in Gcal ha^{-1}) simulated for the historic and the +2°C period with the BAU scenario (blue and red crossbars, respectively); mean and 5th to 95th percentile ranges are plotted. Numbers below crossbars represent mean yield change in Gcal ha^{-1} and % relative to the historic baseline. All changes are statistically significant (the paired *t*-test $P<0.001$) – more details in Table S3 in the Supporting Information.

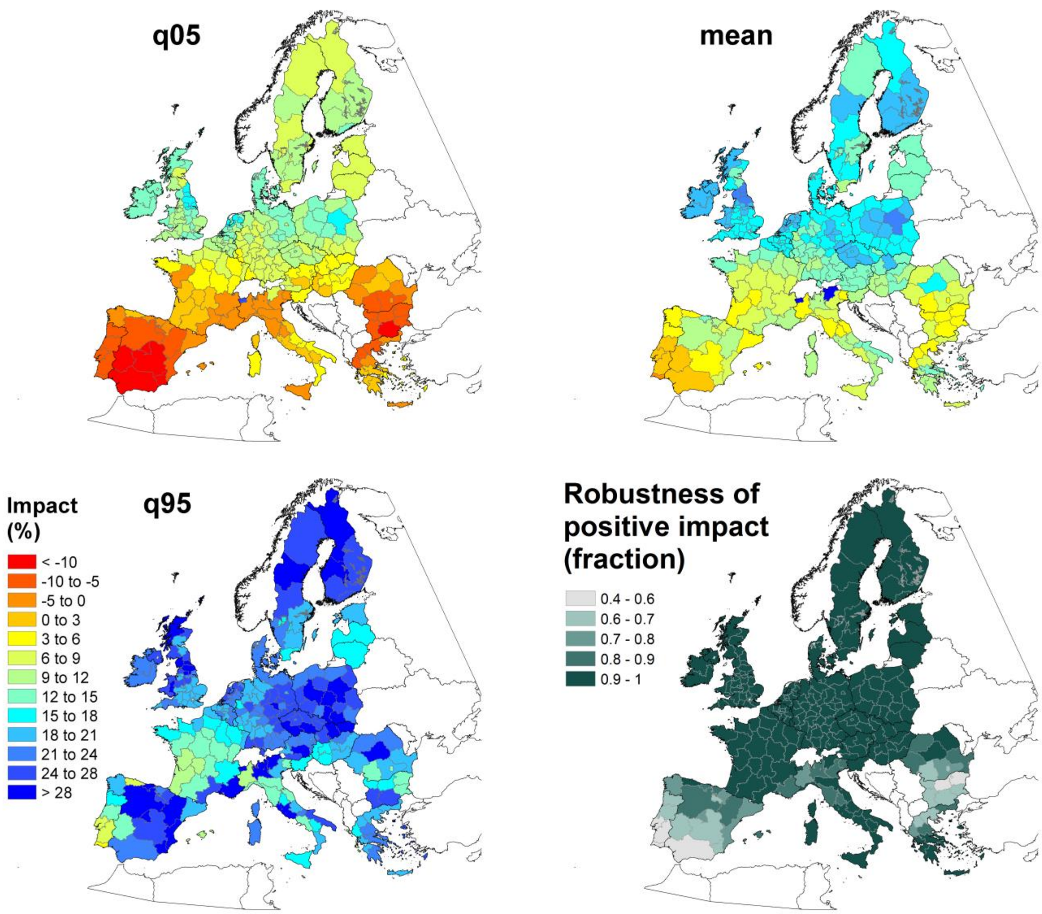
Figure 2 Calorie yield impact of a +2°C global warming on crop calorie yield (ensemble mean, 5th and 95th percentiles) and robustness of the positive impact in the ensemble simulations.

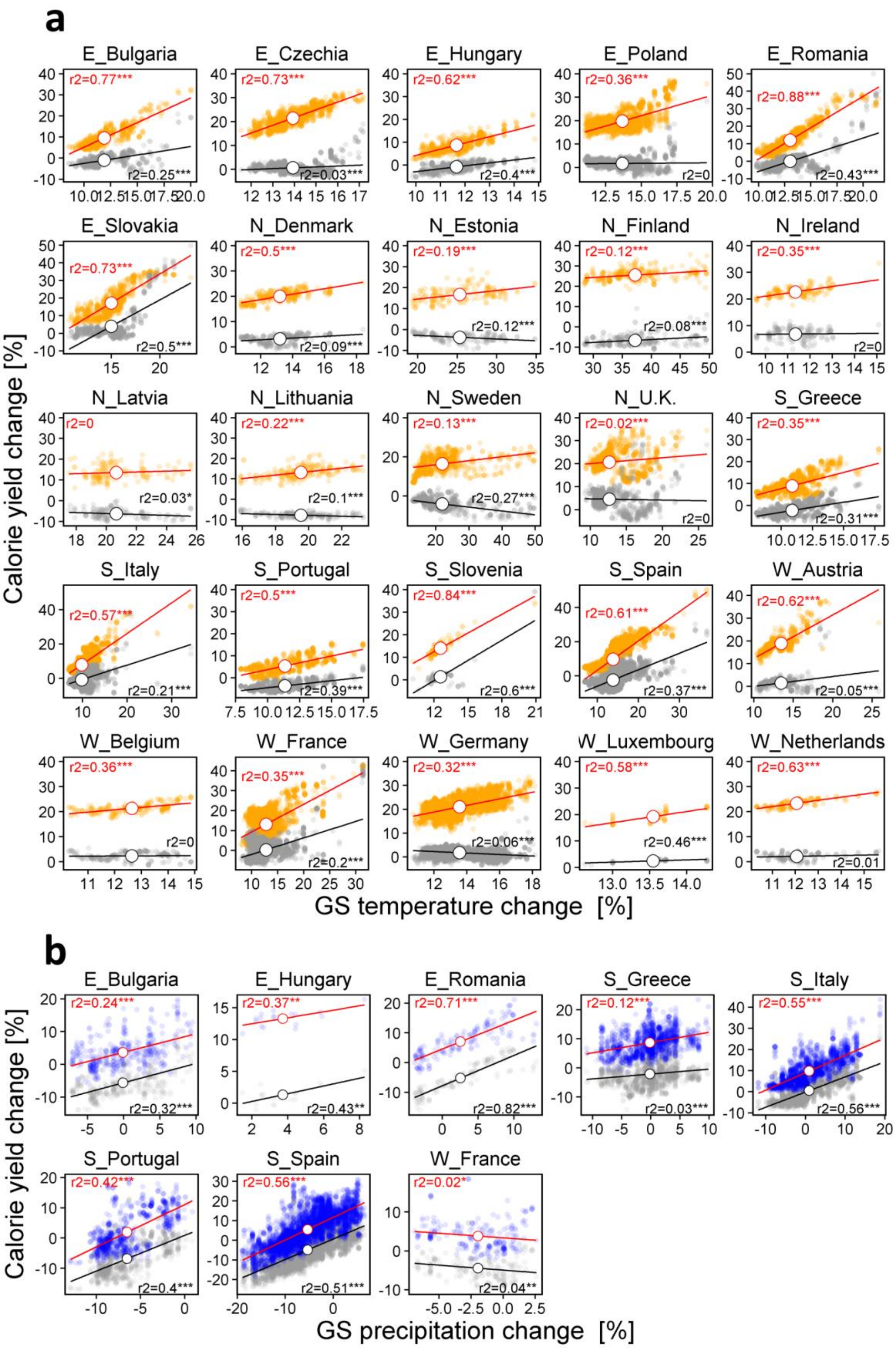
Figure 3. (a) Calorie yield response to changes in the growing season (GS) temperature sums in temperature-limited production systems, and (b) calorie yield response to changes in the GS precipitation sums in water-limited production systems. Data points represent ensemble-mean impacts (in %) or transient CO_2 (orange, blue) and fixed CO_2 levels (grey); circle markers demonstrate respective mean changes at the national level. The differences between simulations with transient and fixed CO_2 are statistically significant in all the plots (the paired *t*-test $P < 0.001$). Prefix letters denote the geographic region (e.g. N = Northern European countries).

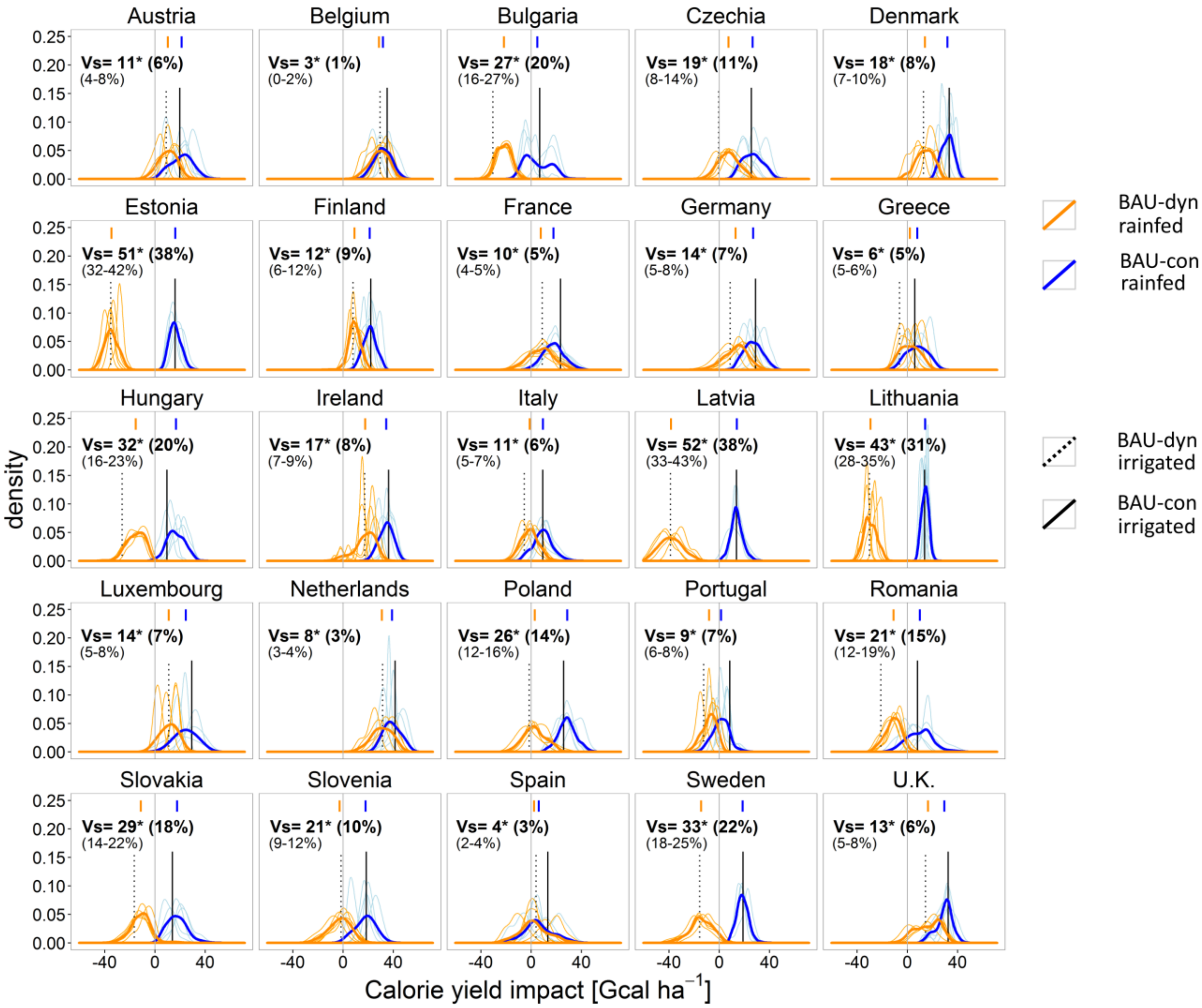
Figure 4 Crop calorie yield impact distribution under scenario with (BAU-*dyn*, orange) and without (BAU-*con*, blue) soil degradation (mean values are portrayed as lines in the respective colours on the top). Vulnerability to soil degradation (*Vs* in Gcal ha^{-1} and %) are denoted by asterisk where statistically significant at $P<0.001$. The black lines indicate mean calorie yields estimated for irrigated systems with (dotted) and without (solid) soil degradation under the BAU scenario. Calorie yield impacts calculated for individual climatic projections are portrayed as thin lines in the respective colours.

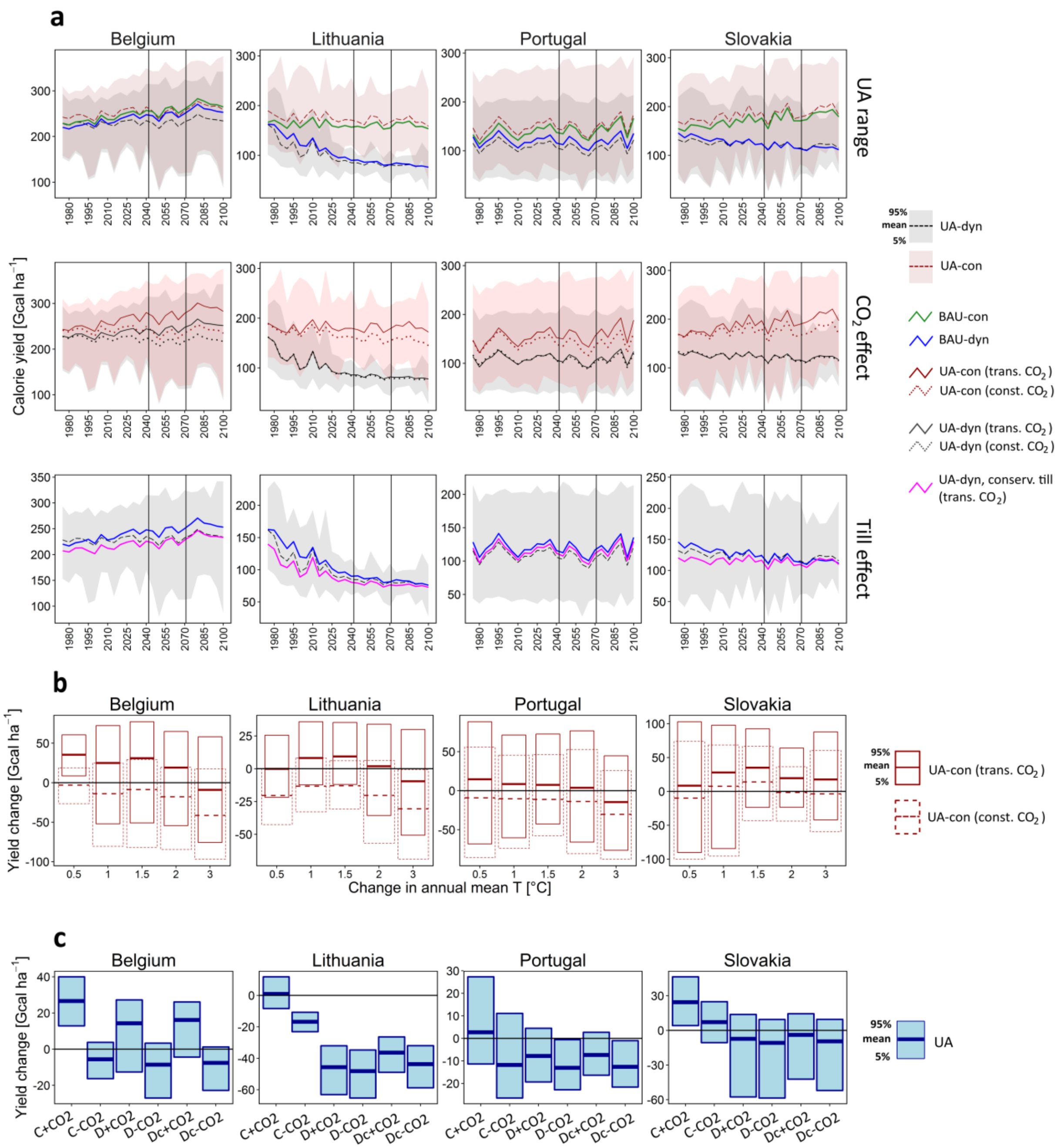
Figure 5 (a) Uncertainty range of simulated crop calorie yield under different soil degradation and atmospheric CO_2 assumptions calculated for Belgium, Lithuania, Portugal and Slovakia under the KNMI climate ensemble member. Grey and red shadings represent the yield uncertainty ranges calculated for the *dyn* and *con* soil handling scenarios, respectively (black and red dashed lines demonstrate the UA average); blue and green lines represent the mean yields calculated under the *dyn* and *con* scenarios, respectively, used for the *Vs* analysis in Section 3.3. The vertical black lines portray the corresponding +2°C period in KNMI. (b) the UA range of yield change (in Gcal ha^{-1}) relative to the historical average (1971–2000) simulated for different regional warming levels occurring within the +2°C of global warming period. (c) the UA yield change range (in Gcal ha^{-1}) relative to the historical period simulated with no-degradation (C) and degradation (D) scenarios, with constant (–) and transient (+) atmospheric CO_2, and with soil conservation practices (Dc) in the degradation scenario.


Calorie yield [Gcal ha^{-1}]
Eastern EU
Northern EU
Southern EU
Western EU
Bulgaria
Czechia
Hungary
Poland
Romania
Slovakia
Denmark
Estonia
Finland
Ireland
Lithuania
Latvia
Sweden
U.K.
Spain
Greece
Italy
Portugal
Slovenia
Austria
Belgium
Germany
France
Luxembourg
Netherlands
95%
mean
5%
+2°C, BAU
HIS, BAU


q05
mean
Impact
(%)
q95
< -10
-10 to -5
-5 to 0
0 to 3
3 to 6
6 to 9
9 to 12
12 to 15
15 to 18
18 to 21
21 to 24
24 to 28
> 28
Robustness of
positive impact
(fraction)
0.4 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1


a
E_Bulgaria
r2=0.77***
r2=0.25***
E_Czechia
r2=0.73***
r2=0.03***
E_Hungary
r2=0.62***
r2=0.4***
E_Poland
r2=0.36***
r2=0
E_Romania
r2=0.88***
r2=0.43***
E_Slovakia
r2=0.73***
r2=0.5***
N_Denmark
r2=0.5***
r2=0.09***
N_Estonia
r2=0.19***
r2=0.12***
N_Finland
r2=0.12***
r2=0.08***
N_Ireland
r2=0.35***
r2=0
N_Latvia
r2=0
r2=0.03*
N_Lithuania
r2=0.22***
r2=0.1***
N_Sweden
r2=0.13***
r2=0.27***
N_U.K.
r2=0.02***
r2=0
S_Greece
r2=0.35***
r2=0.31***
S_Italy
r2=0.57***
r2=0.21***
S_Portugal
r2=0.5***
r2=0.39***
S_Slovenia
r2=0.84***
r2=0.6***
S_Spain
r2=0.61***
r2=0.37***
W_Austria
r2=0.62***
r2=0.05***
W_Belgium
r2=0.36***
r2=0
W_France
r2=0.35***
r2=0.2***
W_Germany
r2=0.32***
r2=0.06***
W_Luxembourg
r2=0.58***
r2=0.46***
W_Netherlands
r2=0.63***
r2=0.01
Calorie yield change [%]
GS temperature change [%]
b
E_Bulgaria
r2=0.24***
r2=0.32***
E_Hungary
r2=0.37**
r2=0.43**
E_Romania
r2=0.71***
r2=0.82***
S_Greece
r2=0.12***
r2=0.03***
S_Italy
r2=0.55***
r2=0.56***
S_Portugal
r2=0.42***
r2=0.4***
S_Spain
r2=0.56***
r2=0.51***
W_France
r2=0.02*
r2=0.04**
Calorie yield change [%]
GS precipitation change [%]


Austria
Vs= 11* (6%)
(4-8%)
Belgium
Vs= 3* (1%)
(0-2%)
Bulgaria
Vs= 27* (20%)
(16-27%)
Czechia
Vs= 19* (11%)
(8-14%)
Denmark
Vs= 18* (8%)
(7-10%)
Estonia
Vs= 51* (38%)
(32-42%)
Finland
Vs= 12* (9%)
(6-12%)
France
Vs= 10* (5%)
(4-5%)
Germany
Vs= 14* (7%)
(5-8%)
Greece
Vs= 6* (5%)
(5-6%)
Hungary
Vs= 32* (20%)
(16-23%)
Ireland
Vs= 17* (8%)
(7-9%)
Italy
Vs= 11* (6%)
(5-7%)
Latvia
Vs= 52* (38%)
(33-43%)
Lithuania
Vs= 43* (31%)
(28-35%)
Luxembourg
Vs= 14* (7%)
(5-8%)
Netherlands
Vs= 8* (3%)
(3-4%)
Poland
Vs= 26* (14%)
(12-16%)
Portugal
Vs= 9* (7%)
(6-8%)
Romania
Vs= 21* (15%)
(12-19%)
Slovakia
Vs= 29* (18%)
(14-22%)
Slovenia
Vs= 21* (10%)
(9-12%)
Spain
Vs= 4* (3%)
(2-4%)
Sweden
Vs= 33* (22%)
(18-25%)
U.K.
Vs= 13* (6%)
(5-8%)
density
Calorie yield impact [Gcal ha^{-1}]
BAU-dyn rainfed
BAU-con rainfed
BAU-dyn irrigated
BAU-con irrigated


a
Belgium
Lithuania
Portugal
Slovakia
UA range
CO2 effect
Till effect
Calorie yield [Gcal ha-1]
95%
mean
5%
UA-dyn
UA-con
BAU-con
BAU-dyn
UA-con (trans. CO2)
UA-con (const. CO2)
UA-dyn (trans. CO2)
UA-dyn (const. CO2)
UA-dyn, conserv. till (trans. CO2)
b
Belgium
Lithuania
Portugal
Slovakia
Yield change [Gcal ha-1]
Change in annual mean T [°C]
95%
mean
5%
UA-con (trans. CO2)
UA-con (const. CO2)
c
Belgium
Lithuania
Portugal
Slovakia
Yield change [Gcal ha-1]
C+CO2
C-CO2
D+CO2
D-CO2
Dc+CO2
Dc-CO2
95%
mean
5%
UA