

RESEARCH ARTICLE

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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 Folberth¹, Nikolay Khabarov¹, Erwin Schmid⁴, Mikuláš Madaras⁵, Michael Obersteiner¹, and Marijn van der Velde⁶

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 CO₂ effect
- Soil degradation could undermine climate-related benefits in Eastern and North-Eastern Europe

Supporting Information:

- Supporting Information S1.

Correspondence to:

Juraj Balkovič, balkovic@iiasa.ac.at

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¹International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Laxenburg, Austria, ²Department of Soil Science, Faculty of Natural Sciences, Comenius University in Bratislava, Bratislava, Slovak Republic, ³National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Bratislava, Slovak Republic, ⁴Institute for Sustainable Economic Development, University of Natural Resource and Life Sciences, Vienna, Vienna, Austria, ⁵Division of Crop Management Systems, Crop Research Institute, Prague, Czech Republic, ⁶European Commission, Joint Research Centre, Ispra, Italy

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 10 major crops and vulnerability to soil degradation in Europe using crop modeling. The Environmental Policy Integrated Climate (EPIC) model together with regional climate projections from the European branch of the Coordinated Regional Downscaling Experiment (EURO-CORDEX) was 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 CO₂ and increased temperature are the dominant drivers of the simulated yield changes in high-input agricultural systems. The growth stimulus due to elevated CO₂ 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 50 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 2–50 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 global 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 (CO₂) 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 CO₂ concentration (Asseng et al., 2015; Kimball, 2016; Long et al., 2006), soil heterogeneity (Folberth 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 endeavor 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 10 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 modeling are quantified via an uncertainty analysis (UA) 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 CO₂ effects, and (3) uncertainty in soil degradation modeling.

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 (Izaurre 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 vapor pressure deficit and atmospheric CO₂ 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 aluminum

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. Projection name (regional/global climate model): CSC-REMO/MPI-ESM-LR (RCP 4.5) SMHI-RCA4/EC-EARTH (RCP 4.5) KNMI-RACMO22E/EC-EARTH (RCP 4.5) SMHI-RCA4/HadGEM2-ES (RCP 4.5) IPSL-WRF331F/IPSL-CM5A-MR (RCP 4.5) | 0.11 arc-degree | Daily, all projections from 1971 to 2100 +2°C interval: 2050–2079 2042–2071 2042–2071 2023–2052 2028–2057 | The Quantifying Projected Impacts Under 2°C Warming (IMPACT2C) Project (http://impact2c.hzg.de) EURO-CORDEX data: http://www.euro-cordex.net |
| Terrain | Shuttle Radar Topographic Mission Data (SRTM) | 3" | N/A | Werner (2001) |
| Soil | Global 30 Arc Second Elevation Data (GTOPO) | 30" | N/A | http://eros.usgs.gov |
| | 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 subnational 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 | | | http://ec.europa.eu/eurostat/web/nuts/overview |
| Management | Crop sowing dates | 50 km | around 2000 | www.eea.europa.eu |
| | Regional N and P fertilization rates (mineral + organic) | NUTS2 regions | around 2000 | Balković et al. (2013) |
| | Statistics on crop yields | NUTS2 regions | 1996–2007 | Balković et al. (2013) |
| | European Irrigation Map (EIM) | 1 ha | around 2000 | EUROSTAT Wriedt et al. (2009) |

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 reinitialized 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 et al. (2016) based on the aforementioned references.

The biophysical EPIC v.0810 model was coupled with ArcGIS and a gridded modeling 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 CO₂ 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 postmaturity 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 Supporting Information S1 (Text S1, Figure S9, and Table S4). Parameters used to describe crop's growth characteristics and their response to increased atmospheric CO₂ are summarized in Table S5 in Supporting Information S1.

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 modeling 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 preindustrial 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 CO₂ concentration increases from about 360 ppm around the year 2000 up to concentration of 470–580 ppm at the +2°C threshold.

2.3. Crop Management Scenarios

A total of three crop management scenarios were designed to analyze 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 subnational statistical regions (NUTS2). Crop-specific annual

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 ($\text{kg ha}^{-1} \text{ a}^{-1}$) | P per crop ($\text{kg ha}^{-1} \text{ a}^{-1}$) |
|----------|-------------------------|--|------------------------|--|--|
| | | Presently rainfed | Presently irrigated | | |
| BAU | Crop-specific | 0 | 1000 ^b | BAU | BAU |
| P1 | All equipped cropland | 0 | 1000 ^b | Max. 250 | Automatic |
| P2 | All cropland | 1000 ^b | 1000 ^b | Max. 250 | Automatic |

^bThe upper limit of irrigation water supply (simulated irrigation water volume is less or equals 1000 mm a^{-1}).

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 kilograms 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 result, 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 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 $1000 \text{ mm crop}^{-1}$ (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).

- 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 $250 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ 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 $250 \text{ kg ha}^{-1} \text{ crop}^{-1}$. 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.
- 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 reinitialized 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 S1.

All simulations were carried out assuming conventional tillage, consisting of two cultivation operations and moldboard plowing 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 plow with high mixing efficiency.

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 equation 1. The y values were summed across all crops and converted to the combined calorie yield (Y) by equation 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 in Supporting Information 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.

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

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

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 S1. Yield vulnerability (V_s) is quantified as a fraction of projected calorie yield that may be lost due to harmful effects of soil degradation. BAU 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 (equation 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 equation 3.

$$V_{s,p} = I(\text{con})_{p,s} - I(\text{dyn})_{p,s} \quad (3)$$

where I is 30-year mean yield impact (in Gcal ha^{-1}) of $+2^\circ$ 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 UA (Section 2.6.1).

2.6. Evaluation of Uncertainties in the Modeling Approach

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

2.6.1. Evaluation of Uncertainties in Modeling Temperature, CO_2 , and Soil Degradation Effects

We performed a detailed 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 biogeochemical 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 \times 4790 SimUs \times 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 analyzed by grouping all yield data simulated for the $+2^\circ\text{C}$ 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 modeling 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 S1.

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 ^b | 1,2 ^b |
| 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) |

BAU = business-as-usual.
^bcrop-specific number.

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 subnational level. Figure 1 demonstrates yield ranges estimated from the full ensemble of climate projections under the BAU scenario and transient atmospheric CO₂ 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 subnational level (NUTS2 regions) in Figure 2. Mean calorie yield changes for individual ensemble members are presented in Table S3 in the Supporting Information S1.

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, United Kingdom 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 in Supporting Information S1.

At the national level, an increase by 17–38 Gcal ha⁻¹ was estimated for Western European countries, that is, countries which currently belong to the most productive in Europe. The lowest but still robustly estimated positive impact was approximately 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

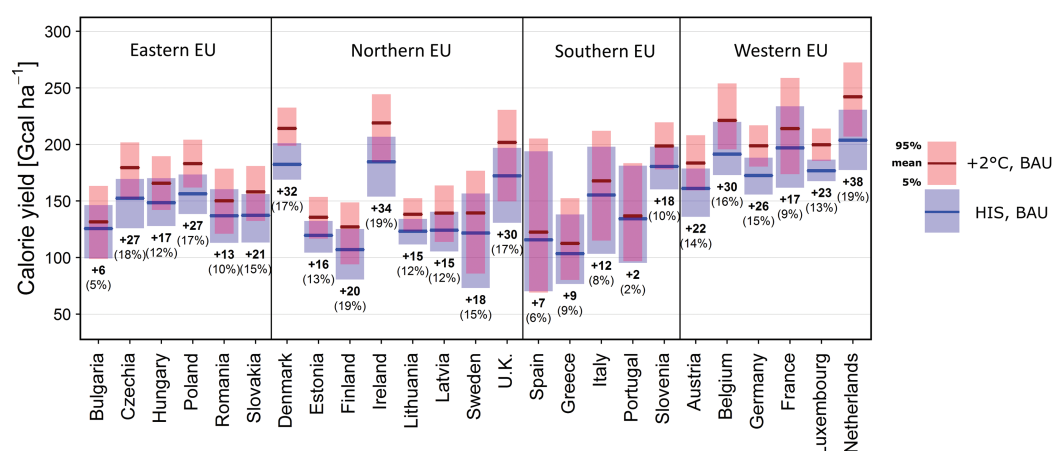


Figure 1. Crop calorie yield (in Gcal ha^{-1}) simulated for the historic and the $+2^\circ\text{C}$ period with the BAU scenario (blue and red crossbars, respectively); mean and 5th to 95th percentile ranges are plotted. Numbers below crossbars represent mean yield change in Gcal ha^{-1} and % relative to the historic baseline. All changes are statistically significant (the paired t -test $p < .001$)—more details in Table S3 in the Supporting Information S1.

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 and Table S2 in Supporting Information S1).

In the countries of the Balkan Peninsula, at the national average, a small overall increase of 6–13 Gcal ha^{-1} was calculated, while for the other Eastern European countries a moderate gain of 17–27 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 in Supporting Information 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 subnational calorie yield changes ranged between strongly negative of -20% and positive of up to 35% (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, while 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 in Supporting Information S1) and (2) more favorable 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

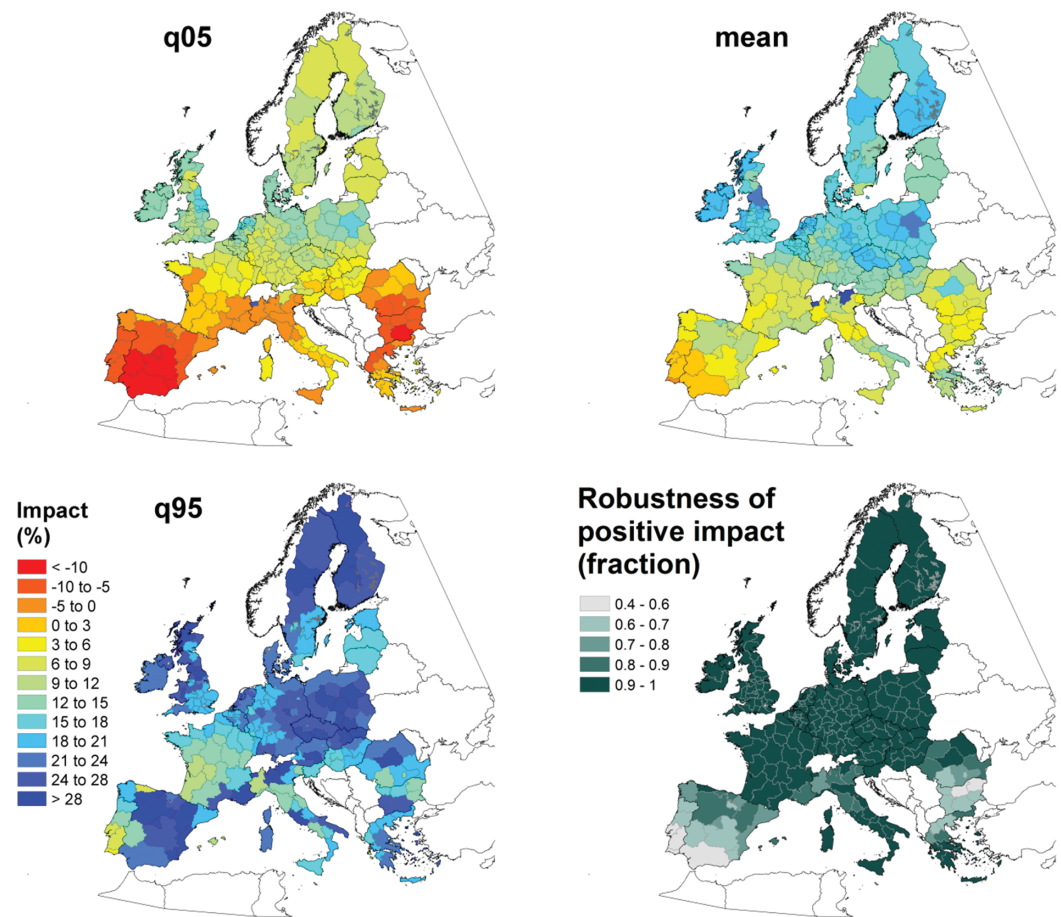


Figure 2. Calorie yield impact of a +2°C global warming on crop calorie yield (ensemble mean, 5th and 95th percentiles) and robustness of the positive impact in the ensemble simulations.

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 ($r^2 < .4$ 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 approximately 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 in Supporting Information S1).

A positive effect of increased temperature under elevated CO_2 was simulated also for irrigated and high-rainfall crops in Eastern Europe ($r^2 > .6$ in all countries except for Poland in Figure 3a). A approximately 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

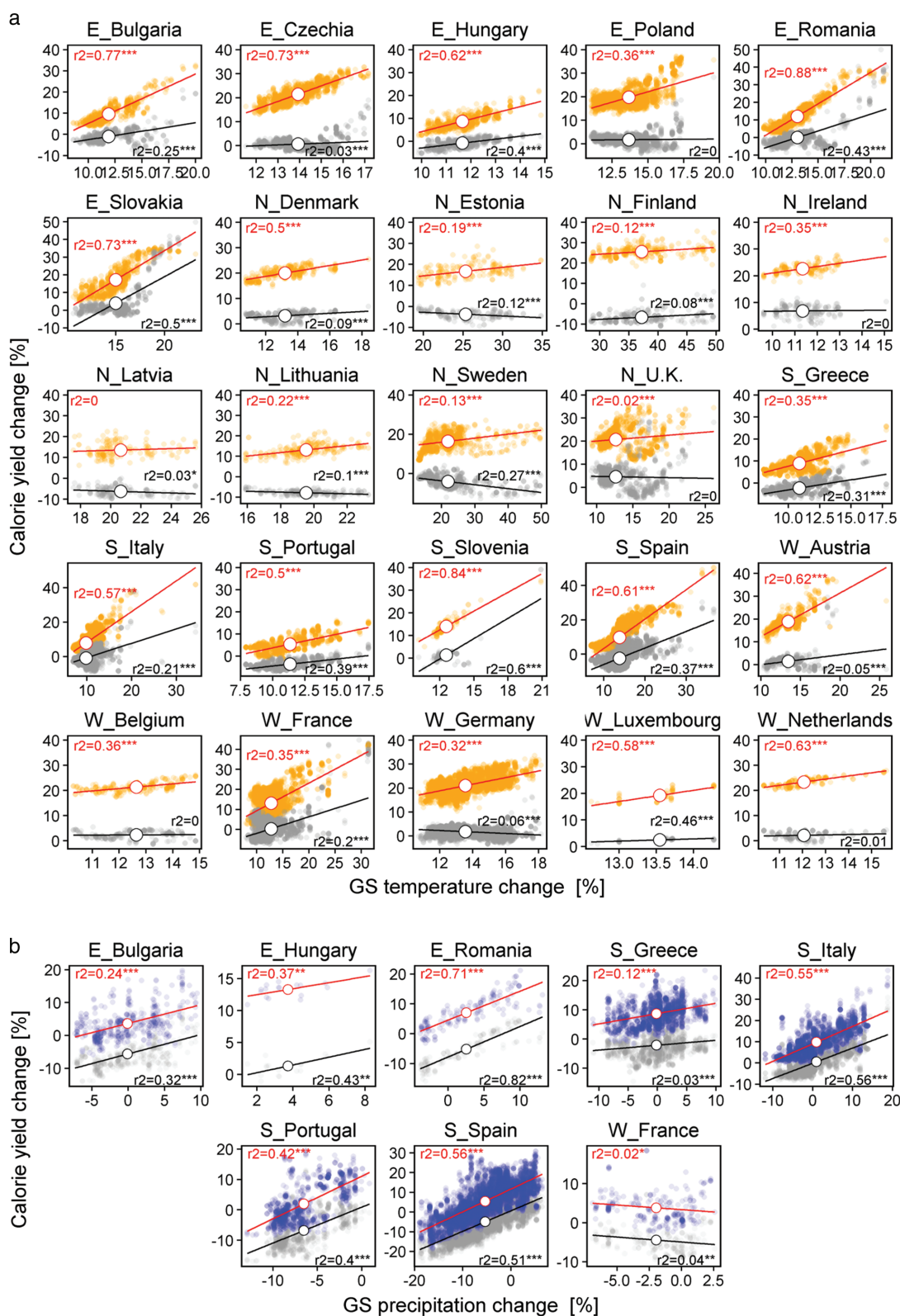


Figure 3. (a) Calorie yield response to changes in the growing season (GS) temperature sums in temperature-limited production systems, and (b) calorie yield response to changes in the GS precipitation sums in water-limited production systems. Data points represent ensemble-mean impacts (in %) simulated with transient CO_2 (orange, blue) and fixed CO_2 levels (gray); 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 $p < .001$). Prefix letters denote the geographic region (e.g., N = Northern European countries).

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 in Supporting Information S1). 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 Supporting Information S1). 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 in Supporting Information S1). Dryland areas would also significantly benefit from elevated CO_2 , potentially offsetting the yield losses corresponding to a precipitation decrease by approximately 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 100–200 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 $p < .001$ 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 in Supporting Information S1). The estimates in Figure 3b indicate that elevated CO_2 may potentially offset calorie losses corresponding to a precipitation decrease by approximately 10% in the Mediterranean dryland.

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 do not 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 in Supporting Information S1). 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 in Supporting Information S1), nutrient inputs would not sufficiently compensate for weakening soil fertility under $+2^\circ\text{C}$. An even higher vulnerability of above 40 Gcal ha^{-1} was simulated for the Baltic states with soil carbon loss due to warmer climate (Figure S5 in Supporting Information S1) 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 $+2^\circ\text{C}$ 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 Supporting Information S1). 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).

Due to low level of fertilization, yield vulnerability at $+2^\circ\text{C}$ is largely driven by decreasing soil organic matter in the Baltic states and Eastern Europe (Figure S5 in Supporting Information S1). 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 in Supporting Information S1). Losses of more than 100 t ha^{-1} in extreme years were simulated especially in the Mediterranean countries (see 99th percentiles

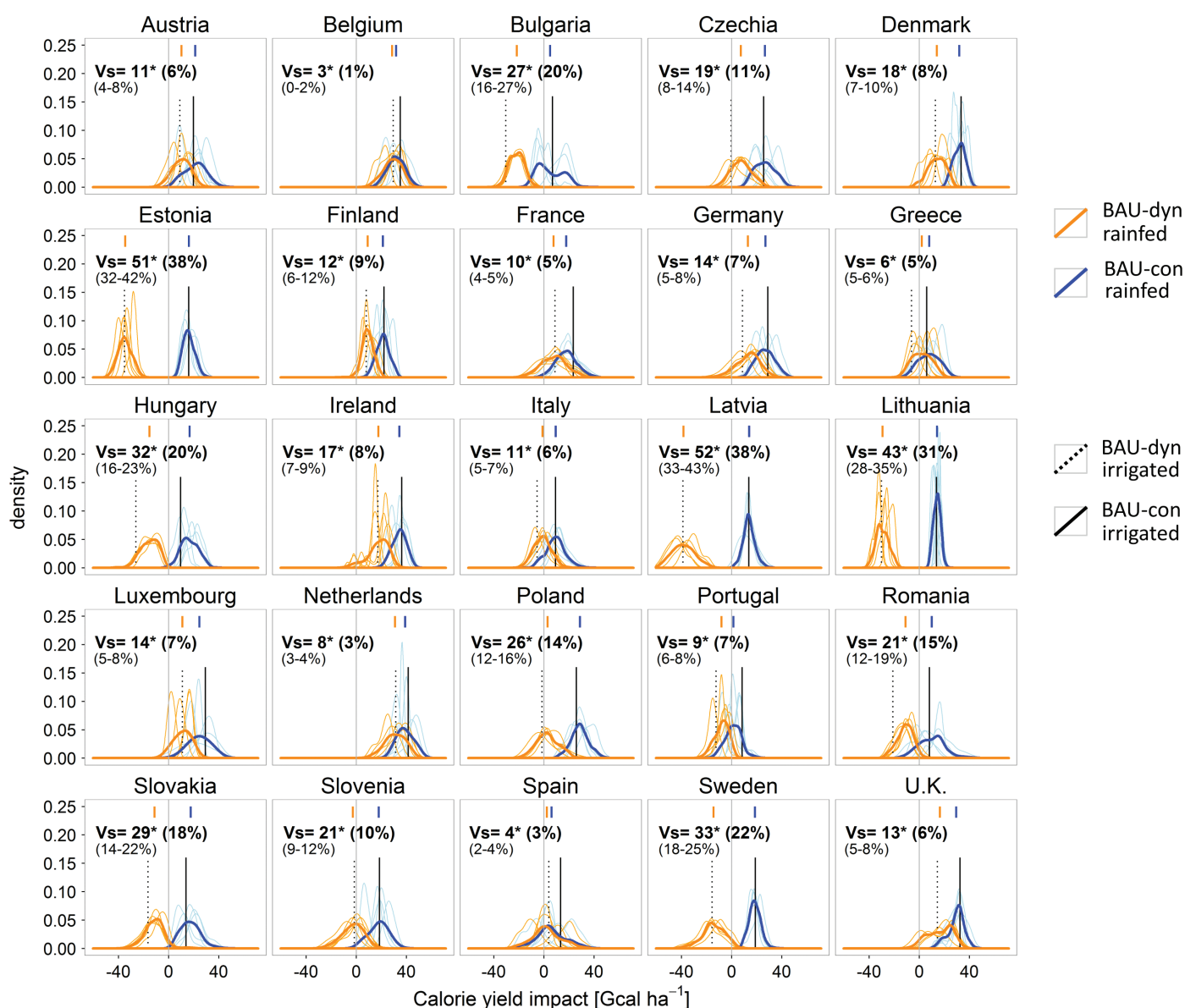


Figure 4. Crop calorie yield impact distribution under scenario with (BAU-dyn, orange) and without (BAU-con, blue) soil degradation (mean values are portrayed as lines in the respective colors on the top). Vulnerability to soil degradation (Vs in Gcal ha⁻¹ and %) are denoted by asterisk where statistically significant at $p < .001$. 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 colors.

in Table S6 in Supporting Information S1). However, erosion contributed only little to the national yield vulnerability under +2°C. As demonstrated in Figure S6 in Supporting Information S1, 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 severe 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 in Supporting Information S1).

3.4. Uncertainty Due to Modeling Temperature, CO₂, 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 color, respectively) are located roughly in the mid-range of the respective soil handling scenarios (con and dyn in red and gray colors, respectively). Figure 5a demonstrates yield uncertainty

induced by (1) varied model parameters and inputs, (2) atmospheric CO₂ 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 in Supporting Information S1). 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 $+2^{\circ}\text{C}$ period relative to the respective historic period, is substantial for all analyzed 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 $+2^{\circ}\text{C}$ 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%–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, while 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 CO₂ stimulated calories by 40 Gcal ha⁻¹ in Belgium, where crops largely benefit from direct CO₂ 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 CO₂-induced yield gain is lower (~ 20 Gcal ha⁻¹) under no degradation, and there is no effect in the degradation scenario (Figure 5a, "CO₂ effect" panel). With atmospheric CO₂ fixed at 360 ppm, rising temperature would have a negative effect on simulated mean calorie yield in all analyzed 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 $+2^{\circ}\text{C}$ of regional warming is considered. Elevated CO₂ (490–605 ppm in the $+2^{\circ}\text{C}$ period) significantly increased calorie yields in all countries and warming intervals (ΔT) compared to constant CO₂ scenario (paired *t*-test $p < .001$). Importantly, the growth increment due to CO₂ elevated by approximately 200 ppm offset temperature increase of $+2^{\circ}\text{C}$ 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 CO₂ overcompensated the negative impacts of local $+2^{\circ}\text{C}$ warming across the whole range of UA in Lithuania and to a lesser extent in other analyzed countries under the no-degradation scenario (C + CO₂ versus C – CO₂ in Figure 5c). Soil degradation (D + CO₂) robustly decreased the CO₂-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 CO₂ is only marginal under the degradation scenario in Lithuania, Slovakia, and Portugal where yields are dominated by nutrient limitations, and CO₂ cannot compensate for the combined effect of warming and degradation (D + CO₂ and D – CO₂ 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 analyzed countries under both CO₂ scenarios.

3.5. Bracketing Crop Intensification Uncertainties

Extrapolation of BAU crop fertilization and irrigation management toward the time period of the $+2^{\circ}\text{C}$ 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 2 (e.g., Belgium and Netherlands) to 50 (Portugal) times higher than the projected climate impacts presented in Section 3.1,

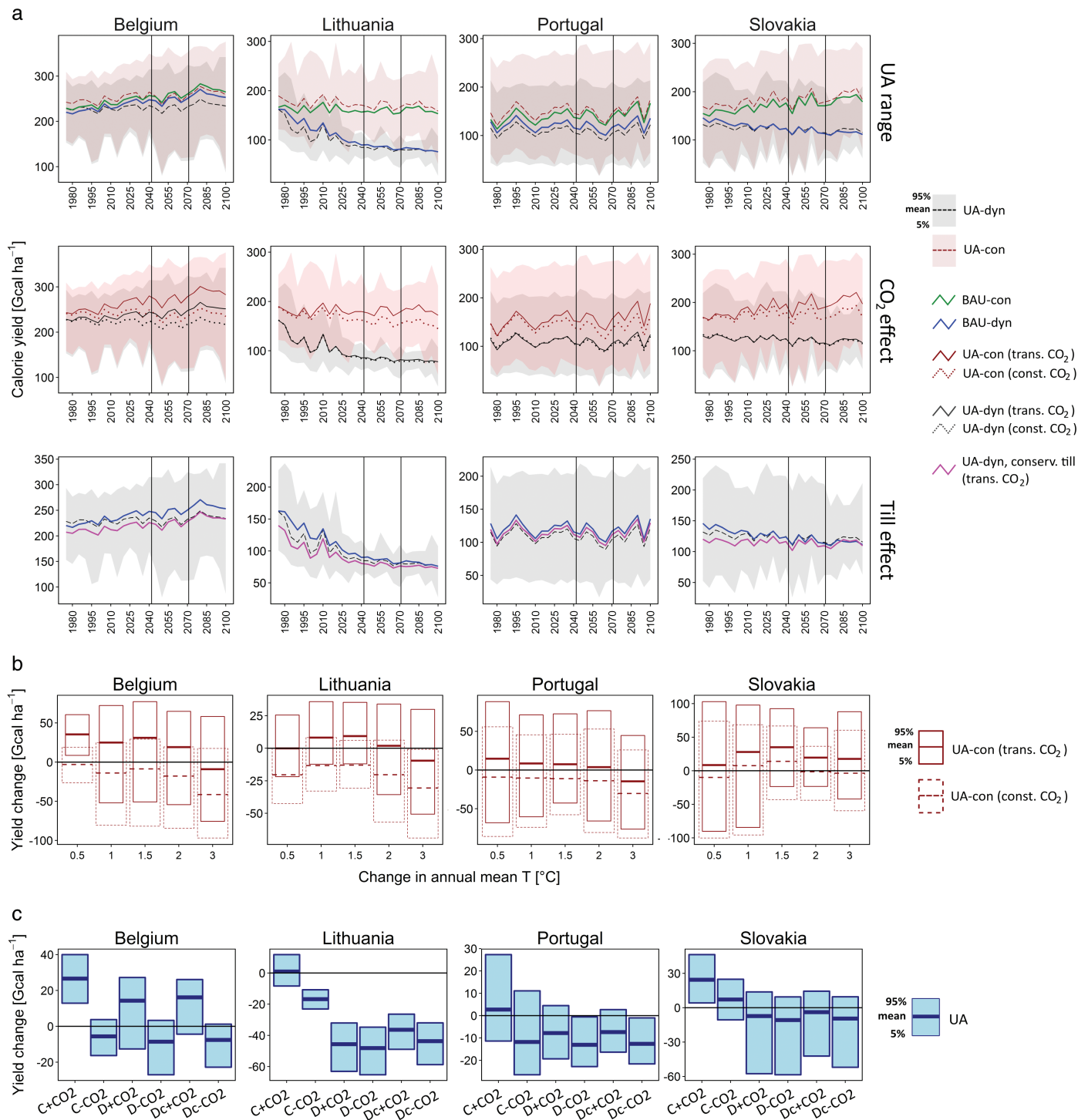


Table 4.

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)

| | | Scenario P1 | | Scenario P2 | |
|-----------------|-------------|-----------------------|----|-----------------------|-----|
| | Country | 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 |
| | Austria | 52 | 28 | 82 | 44 |
| Western Europe | 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 |

All differences are statistically significant (the paired *t*-test *p* < .001)

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).

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 in Supporting Information S1).

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 Supporting Information S1). 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 annual irrigation water requirement of 140–200 mm crop⁻¹ on average, and more than 250 mm crop⁻¹ in some regions (Figure S8b in Supporting Information S1) 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 annual irrigation requirement of more than 250 mm crop⁻¹ (160 mm in Italy and 60 mm in Slovenia) on almost all available cropland (Figure S8b in Supporting Information S1).

4. Discussion

BAU crop management with transient CO₂ 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 CO₂ agree with general expectations of:

1. a positive effect of warming and elevated CO₂ 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. CO₂-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 CO₂ Effect

Our simulations suggest that direct fertilization effect of rising CO₂ 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 UA 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 CO₂. Long et al. (2006) raised concern that biophysical models including EPIC may overestimate (by ~50%) the direct CO₂ fertilization effects, which was later disputed (Ewert et al., 2007; Kimball, 2016; Tubiello et al., 2007). Figure S10 in Supporting Information S1 demonstrates, in a generic way, how the most important crops (C₃ wheat and C₄ maize) respond to temperature increase and elevated CO₂ in our pan-EU EPIC, allowing comparison to published outcomes. In summary, our results agree fairly well with temperature and elevated CO₂ effects experienced in field experiments and field-scale modeling:

1. A negative response of wheat yields to increasing temperature at the current atmospheric CO₂ 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 in Supporting Information S1), 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 CO₂ at present temperature as simulated by EPIC (+0°C bin in Figure S10a and S10b in Supporting Information S1) 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 CO₂ were also reported for other C₃ crops, including rice and barley, soybean, potatoes and sugar beet by Kimball (2016).
 3. A higher response to elevated CO₂ 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 CO₂ fertilization and reduced transpiration may partly off-set negative impacts on C₃ crops in dry regions, although the full advantage from elevated CO₂ 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 approximately 10% increase due to CO₂ 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 CO₂ 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 CO₂ may contribute to canceling out the negative effects of warming, especially in Southern Europe (Figure S10c and S10d in Supporting Information S1).

4.2. Soil Degradation Concept

Future soil degradation and its impacts on crop production are 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 in Supporting Information S1). 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 in Supporting Information S1). On the contrary, irrigation intensity has only a small effect on yield vulnerability (Figure S3b in Supporting Information S1), 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 in Supporting Information S1). More detailed description and discussion with this respect is provided in Text S3 in Supporting Information S1. 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 soil organic matter 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 our vulnerability assessment in Section 3.3. We examine possible implications of avoiding conservation practices for our analysis in Section 3.4 by analyzing the calorie yields simulated under assumptions of (1) low intensity of soil disturbance, (2) high crop residue return, (3) mulching, (4) manure fertilization, and (5) high erosion control (see Table 3), that is, 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%–95% of conventional yields (de Ponti et al., 2012; Soane et al., 2012), and the relative loss is higher in cooler regions (Lithuania),

while 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 approximately 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 $5 \text{ t ha}^{-1} \text{ a}^{-1}$ (data not shown), while Panagos et al. (2015) reported approximately 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 in Supporting Information S1), 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 $+2^\circ\text{C}$ (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 toward 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 approximately 80% of the yield potential can be utilized by farmers (Lobell et al., 2009; van Ittersum et al., 2013), the BAU fertilization already provides sufficient supply to capitalize from $+2^\circ\text{C}$ 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 $+2^\circ\text{C}$ 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 in Supporting Information S1). 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 Modeling 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 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 in Supporting Information S1) 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 CO₂ 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 concerns (Folberth et al., 2016). Given the limitations on both sides, the skills of pan-European EPIC against the multimodel approach should be explored.

5. Conclusions

Assuming current crop management practices and increasing CO₂ concentrations, a robustly positive calorie yield change of 5%–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 (from –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) CO₂ fertilization effect and (2) improved growing season temperatures for summer crops in Northern Europe and in higher altitudes. The projections suggest that 100–200 ppm more CO₂ 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 CO₂. For example, the impacts on temperature-limited systems would be considerably smaller, but still mostly positive, when only approximately 50% efficiency of CO₂ 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 CO₂ 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 CO₂ 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 do not have the capacity to (1) overcompensate for losses due to nutrient depletion and (2) benefit from rising CO₂ 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 in Supporting Information S1), the vulnerability analysis is burdened by a considerable uncertainty due to modeling 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 2–50 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.

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