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Effects of climate change in European croplands and grasslands: productivity, greenhouse gas balance and soil carbon storage

Marco Carozzi^{1,a}, Raphaël Martin², Katja Klumpp², and Raia Silvia Massad¹

¹Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, 78850 Thiverval-Grignon, France

²INRAE, UREP Unité de Recherche sur l'Ecosystème Prairial, 63100 Clermont-Ferrand, France

^anow at: Université Paris-Saclay, INRAE, AgroParisTech, UMR SAD-APT, 78850 Thiverval-Grignon, France

Correspondence: Marco Carozzi (marco.carozzi@inrae.fr)

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Abstract. Knowledge of the effects of climate change on agro-ecosystems is fundamental to identifying local actions aimed to maintain productivity and reduce environmental issues. This study investigates the effects of climate perturbation on the European crop and grassland production systems, combining the findings from two specific biogeochemical models. Accurate and high-resolution management and pedoclimatic data were employed. Results have been verified for the period 1978–2004 (historical period) and projected until 2099 with two divergent intensities: the Intergovernmental Panel on Climate Change (IPCC) climate projections, Representative Concentration Pathway (RCP) 4.5 and RCP8.5. We have provided a detailed overview of productivity and the impacts on management (sowing dates, water demand, nitrogen use efficiency). Biogenic greenhouse gas balance (N₂O, CH₄, CO₂) was calculated, including an assessment of the gases' sensitivity to the leading drivers, and a net carbon budget on production systems was compiled. Results confirmed a rise in productivity in the first half of the century (+5 % for croplands at +0.2 t DM ha⁻¹ yr⁻¹, +1 % for grasslands at +0.1 t DM ha⁻¹ yr⁻¹; DM denotes dry matter), whereas a significant reduction in productivity is expected during the period 2050–2099, caused by the shortening of the length of the plant growing cycle associated with rising temperatures. This effect was more pronounced for the more pessimistic climate scenario (−6.1 % for croplands and −7.7 % for grasslands), for the Mediterranean regions and in central European latitudes, confirming a regionally distributed impact of climate change. Non-CO₂ greenhouse gas emissions were triggered by rising air temperatures and increased exponentially over the century, often exceeding the

CO₂ accumulation of the explored agro-ecosystems, which acted as potential C sinks. The emission factor for N₂O was 1.82 ± 0.07 % during the historical period and rose to up to 2.05 ± 0.11 % for both climate projections. The biomass removal (crop yield, residues exports, mowing and animal intake) converted croplands and grasslands into net C sources (236 ± 107 Tg CO₂ eq. yr⁻¹ in the historical period), increasing from 19 % to 26 % during the climate projections, especially for RCP4.5. Nonetheless, crop residue restitution might represent a potential management strategy to overturn the C balance. Although with a marked latitudinal gradient, water demand will double over the next few decades in the European croplands, whereas the benefit in terms of yield (+2 % to +10 % over the century) will not contribute substantially to balance the C losses due to climate perturbation.

1 Introduction

Agriculture is facing major challenges in meeting growing food demand while limiting soil degradation and air and water pollution and adapting to the impacts of climate change (Chaudhary et al., 2018; Olesen, 2017). The agricultural sector is the main source of non-CO₂ anthropogenic greenhouse gases (GHGs) and is responsible for 78.6 % of nitrous oxide (N₂O) and 39.1 % of methane (CH₄) emissions worldwide (IPCC, 2018). Agricultural practice, which directly affects soil, plants and the atmosphere, represents a strategic lever to counteract climate change by mitigating GHG emissions and fostering soil C storage (Chabbi et al., 2017; Smith et

al., 2008), achieving long-term (i.e. 2100) climate objectives (Fuss et al., 2016; Minasny et al., 2017; Smith et al., 2013).

Evaluating the impacts of climate on agricultural production at local, regional and global scales is still a challenge nowadays (Fitton et al., 2019; Olesen and Bindi, 2002). The main source of uncertainty comes from the representation of agro-ecosystems in models' frameworks or from the approaches used to upscale data networks and local experiments to regional scales (Ewert et al., 2011; Hansen and Jones, 2000; Tubiello et al., 2007). Notwithstanding that, it is commonly recognised that a decrease in crop yields is expected towards the middle and the end of the century, with reductions extending to more than 10 % in some regions of the world (Challinor et al., 2014). A decline in productivity is likely to be combined with an increase in the interannual yield variability due to climate extremes (Dono et al., 2016), with a strong latitudinal gradient (Rosenzweig et al., 2013). In the Northern Hemisphere, which will benefit from the lengthening of the growing season, milder temperatures and wet conditions in the coming decades, crop and grassland production levels are expected to increase (Yang et al., 2015). Conversely, lower latitudes are going to face a rise in drought frequencies with a decline in winter rainfall, accompanied by a potential decline in productivity (Stagge et al., 2017). This geographical divide would lead to intensification of farming systems in northern regions, such as northern Europe, and to extensification in southern regions, such as the Mediterranean Basin (Olesen and Bindi, 2012).

In line with the commitment to the Paris Agreement and the European Green Deal, the European Union (EU) set the objective to cut net GHG emissions by at least 55 % by 2030 compared to 1990 levels. In addition, the EU aims to become climate neutral by 2050 (EC, 2020). These ambitious targets contrast with the agricultural emissions which have stagnated or even increased in the past few years (EEA, 2020). Reducing emissions in agriculture is imperative and implies the use of tailored management options in crop and grassland systems. These options should aim to increase the efficiency of fertilisers, irrigation and feeding strategies; improve the management of crop residues, tillage and drainage; and increase crop diversification in time and space (Aguilera et al., 2013; Conant et al., 2017; Cowan et al., 2016; De Antoni Migliorati et al., 2015; Li et al., 2016; Smith et al., 2008; Smith, 2016; Voglmeier et al., 2019). While there are a consistent number of experimental data regarding the effects of management options at the field scale, robust quantifications of the effects of climate change on actual crop and grassland production systems at the regional scale are still scarce. Concurrently, the need to develop and implement higher-tier methodologies to be applied at fine spatial scales is growing nowadays (Smith, 2012).

Dynamic simulation models are suitable tools to evaluate the multifaceted effects of climate change across agricultural production systems such as croplands and grasslands (Brilli et al., 2017; Ehrhardt et al., 2018; Sándor et al., 2018). Mod-

els are able to isolate the contribution of single or combined factors, trace the evolution of the system components, and observe the aptitude of agricultural strategies to mitigate impacts. More recently, process-based models conceived for site-scale representation have been applied at the regional scales to, for example, calculate national GHG inventories (Smith, 2013) or build statistical models (Del Grosso et al., 2009; Haas et al., 2013). The main challenges to carrying out spatial assessments are represented by the availability and resolution of the input data (Lugato et al., 2014, 2017), by the biases introduced into the aggregation or disaggregation of these data in homogeneous spatial areas (Constantin et al., 2019; Hansen and Jones, 2000), and by the model validity regarding spatial-scale change (Hoffmann et al., 2016). Furthermore, the simulation of agricultural production with climate projections introduces an additional degree of uncertainty that can be reduced with a sound evaluation of historical data (Rosenzweig et al., 2013), as proposed in this study.

This research aims to investigate, by means of process-based simulation models, the contribution and the impacts of climate change in European crop and grassland production systems up to the year 2100. The analysis focuses on plant productivity and the balance of biogenic GHGs (N₂O, CH₄, CO₂), outlining a detailed carbon budget for current agro-ecosystems and with two climate scenarios, one intermediate and one pessimistic. Through a high spatial resolution and detailed management representation, this study provides projections of key agro-ecosystem variables in the near and long term to support the identification of possible actions to maintain productivity and reduce environmental impacts.

2 Material and methods

This study was realised by using two agro-ecosystem models, CERES-EGC (Crop Environment Resource Synthesis – Environnement et Grandes Cultures) (Gabrielle et al., 2005) for cropping systems and the Pasture Simulation (PaSim) model (Riedo et al., 1998) for grassland–livestock systems. These models were run at a spatial resolution of 0.25°, which is equivalent to an aggregation to a squared cell (or “simulation unit”) of 27.78 km sides. Each simulation unit has characteristic soil properties, agricultural management and daily meteorological data. The 0.25° grid has been identified to attain an adequate distribution of the spatial variability in the input data, to attain representativeness of local effects on a European scale and to limit computational burdens (Hoffmann et al., 2016; Constantin et al., 2019). Two distinct periods of temporal aggregation have been considered.

The “historical period”, based on meteorological records, measured soil and management data, outlines the effects of current management on the agro-ecosystems, and is useful for testing the reliability of both models. The “climate scenarios”, based on the same as the historical management practices, trace the near- and long-term impacts of climate

change on the systems under study. These two different aggregation periods are compared to each other to highlight the effects of climate change on the studied systems. Long-term projections are mainly provided to assess the impacts of current management on soil organic carbon storage and GHG emissions.

2.1 Models

The CERES-EGC model was used to simulate croplands in Europe. CERES-EGC is a process-based biogeochemical model in the soil–plant–atmosphere domain adapted from CERES (Jones and Kiniry, 1986). The model is designed to simulate C and N dynamics; heat transfer; and water exchanges from soil, plants and the atmosphere. It works at a daily time step designed to the field scale. Inputs require meteorological and management data as forcing variables and soil and crop data as factors. Meteorological data are constituted by daily minimum and maximum temperature, precipitation, global solar radiation, and wind speed. Management includes tillage, irrigation, fertilisation, information on sowing and incorporation of crop residues. Soil is divided into sublayers with specific depth, physical and chemical characteristics. Simulated crop species include maize (grain and fodder), soft wheat, durum wheat, rye, oat, barley, rapeseed, sorghum, sunflowers, pea, sugar beet and soybean, with the possibility of selecting specific varieties.

Soil C and N dynamics in the ploughed layer are simulated by means of the NCSOIL model (Molina et al., 1983; Nicolardot et al., 1994), which is a nested module in CERES-EGC. NCSOIL computes nitrification, immobilisation and mineralisation of N; the decomposition of soil organic matter (SOM) after incorporation of crop residues; and SOM formation. The module works with a series of specific pools, three pools for crop residues (easily fermentable carbohydrates, cellulose and lignin) and four endogenous pools (zymogenous and microbial biomass, active and passive humus), where CO₂ is released from the decomposition of each pool. N uptake by plants is calculated through a specific supply–demand scheme depending on mineral nitrogen availability and root length density. CERES-EGC includes the model NOE (Hénault et al., 2005) for simulating N₂O emissions from denitrification and nitrification processes in the topsoil (0–20 cm depth). Denitrification and nitrification are computed from a soil-specific potential rate limited by unitless factors related to soil water content, soil temperature and substrate content (nitrates, NO₃, and ammonium, NH₄, for denitrification and nitrification, respectively). Ammonia (NH₃) volatilisation is calculated in a detailed module, while plant growth is simulated according to the crop-specific genetic potential and the photosynthetically active solar radiation absorbed by the canopy. Potential dry matter production is constrained by air temperatures, soil water availability and the N deficit.

PaSim is a biogeochemical process-based model able to simulate C, N and water dynamics in the plant–soil–atmosphere–livestock grassland system (Calanca et al., 2007). Five interacting sub-models of soil biology and physics, microclimate, vegetation, and grazing herbivores constitute the model structure. The model runs on a daily (or hourly) time step, and inputs require soil property data, management and meteorological characteristics (global solar radiation, minimum and maximum air temperature, relative humidity, wind speed, precipitation, and atmospheric CO₂ concentration). The soil is described in six sublayers, allowing us to parameterise different soil depths with site-specific soil physical and chemical characteristics. Management includes grazing, mowing and N fertilisation. Grazing is considered a dairy or suckling system managed by grazing periods with specific stocking density and live weight. Indoor periods are not simulated. Vegetation cover is considered a homogeneous cover with a fixed legume fraction. The vegetation cover comprises the root system and three shoot compartments (laminae, sheaths and stems, and ears) divided into age classes. Soil C dynamics (based on the CENTURY model; Parton et al., 1994) are computed in five pools: a structural and a metabolic pool for fresh organic carbon (plant residues) and an active, a slow and a passive pool for the microbially processed organic carbon. Photosynthetic C is allocated in plant (root and shoot) and can be lost as CO₂ by ecosystem respiration and as CH₄ through enteric fermentation.

Soil N inputs are represented by atmospheric N deposition, symbiotic N₂ fixation, mineral or organic fertilisation, animal faeces, and urine. These inputs, together with the nitrogen mineralised from the organic carbon pools, constitute the mineral N pool. N availability for plants is reduced by losses via processes of immobilisation, NO₃ leaching, NH₃ volatilisation, nitrification and denitrification. N₂O emissions from nitrification and denitrification depends on substrate availability (NO₃ or NH₄). These emissions are modulated by factors controlling the effects of soil temperature and water content. Furthermore, the release of N₂O produced in the soil towards the atmosphere is calculated with a resistance model in the rooting zone and plant canopy (Schmid et al., 2001).

CERES-EGC and PaSim were selected for this evaluation at the regional scale since they have been calibrated and evaluated in different conditions worldwide (Brilli et al., 2017; Ehrhardt et al., 2018; Sándor et al., 2018) and in Europe, i.e. France, Denmark, Germany, Italy, Sweden and the UK for CERES-EGC (Rolland et al., 2008; Lehuger et al., 2009; Wattenbach et al., 2010; Drouet et al., 2011; Lehuger et al., 2011; Goglio et al., 2013; Ferrara et al., 2021; Haas et al., 2021) and France, Germany, Hungary, Ireland, Italy, Portugal, Spain, the Netherlands and the UK for PaSim (Lawton et al., 2006; Calanca et al., 2007; Gottschalk et al., 2007; Vuichard et al., 2007; Ma et al., 2015; Sándor et al., 2016). These models are suitable to simulate a number of crops and rotations, mown or grazed grasslands, and the effects of

management practices on plant–soil–atmosphere–livestock. Besides, they are able to simulate GHG emissions and the carbon budget at the field scale through the C assimilated from photosynthesis; C emitted into the atmosphere from autotrophic and heterotrophic respirations; C recycled (dung, plant residues) or introduced from external sources (fertilisers, soil improvers); and, finally, the C exported from the system by production activities. CO₂ fertilisation was not simulated for croplands (see S4 in the Supplement). Furthermore, the two models used in this study do not represent potential impacts of air pollution and pest and disease effects on plant production.

2.2 Input dataset

2.2.1 Climate data

Historical and climate projection data were used in this study to analyse the likely effect on GHGs, production and soil C stocks in European production systems. We selected two of the four climate scenarios, or Representative Concentration Pathways (RCPs), adopted by the Intergovernmental Panel on Climate Change (IPCC) for the Fifth Assessment Report (AR5) (IPCC, 2013), one intermediate, RCP4.5, and one pessimistic, RCP8.5.

Climate data were provided by the Earth system model HadGEM2-ES (Collins et al., 2011) downscaled to a horizontal grid of a 0.5° side resolution, in the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; Warszawski et al., 2014). Since the spatial resolution of the climatic data is larger than the size selected for the simulation units (0.25°), four adjacent simulation units were subjected to the same meteorological data. Data were not down-scaled to maintain data representativeness and have been shaped for the European surface (29.0 to 71.5° latitude and –24.0 to 45.5° longitude). The HadGEM2-ES model provided daily values of minimum and maximum air temperatures, total precipitation, air specific humidity, short-wave radiation, and near-surface wind speed for the period 1951–2099. Based on these data, input variables for each model were assigned. The simulation protocol consists of a historical dataset, from 1978–2004, constituted in accordance with the HadGEM2-ES model using the historical record of climate forcing factors (Jones et al., 2011) and, from 2005–2099, the two climate projections RCP4.5 and RCP8.5.

2.2.2 Soil data

Soil data were obtained from the European Soil Database (ESDB; Hiederer, 2013). The ESDB is composed of 1 km × 1 km raster files containing topsoil (0 to 30 cm) and subsoil (30 cm to maximum soil depth) data of clay, silt, sand, gravel and soil organic carbon (SOC) content; bulk density; and maximum root depth. Soil pH for the topsoil was derived at the same spatial detail from the ESDB dataset

provided by Reuter et al. (2008). To define the soil characteristics for each spatial simulation unit, the most recurrent soil was selected, based on the above-mentioned characteristics. Organic soils with SOC content greater than 30 kg C m⁻² were excluded (3.4 % of the total simulation units), as well as forest soil. Specific soil inputs were calculated for both models on the basis of the elementary characteristics (see Supplement S1 for details). For both models, a fixed number of six soil layers was established with a thickness defined as a function of the maximum soil depth.

2.2.3 Crop data

Crop species as well as N fertilisation amount were provided in the framework of the GHG-Europe project (EU FP7; Wattenbach et al., 2015) at a spatial resolution of 1 km × 1 km grid. These data are based on the regional statistics of crop distribution (NUTS2 or NUTS0) of the European statistical office (Eurostat, 2019a) and FAOSTAT (2022) databases and on the simulation of the CAPRI model (Common Agricultural Policy Regionalised Impact; Britz and Witzke, 2008; see Leip et al., 2008). The amount of nitrogen fertilisation was provided per crop species at a 1 km × 1 km resolution, while the repartition between mineral and organic nitrogen forms was provided at the NUTS2 scale.

Crop successions were available for the period 1976–2010. We only considered the crop successions from the time interval 1978–2010 since some of the crop species used in the first 2 discarded years were never reused over the time series and represented less than 1 % of the crops in the database (i.e. summer cereal mixes without triticale; other cereals including triticale, winter barley, flax and hemp; and set aside). The two most frequent crop successions were selected as a reference for each simulation unit. Two crop successions from the database were able to cover, on average, up to 93 % of the total agricultural area of each simulation unit. Based on this aggregation, the simulated crops were summer/spring soft wheat, winter soft wheat, durum wheat, summer/spring barley, grain maize, fodder maize, rapeseed, sunflowers, pulses, oat and sugar beet. Crop rotations also included winter rye and potato, which were not explicitly parameterised in the CERES-EGC model and were substituted with specific varieties of soft wheat for rye and of sugar beet for potato. To define the crop species in the period 1951–2099, primary and secondary successions were replicated for all the years preceding and succeeding the time interval of available data (1978–2010). Furthermore, the most adapted and calibrated crop varieties were designated as a function of the latitude, based on previous research and modellers' experience by using the CERES-EGC crop database.

Based on a crop-specific time window and a minimum and maximum threshold temperature, specific sowing dates were defined for each species and year in each simulation unit. Crop-specific windows were extracted from the assessments of USDA (1994) and Sacks (2010), selecting the min-

imum and the maximum typical sowing span over Europe, whereas threshold temperatures were extracted from Steduto et al. (2012). Due to their wide range, the time windows have not been modified over time. The sowing date was set as the earliest possible within the time window, when minimum and maximum temperatures were higher and lower, respectively, than the thresholds. An additional constraint of no precipitation for 3 consecutive days was applied to consider farmers' practice concerning access to the field. If a suitable sowing date was not identified, a fixed date was imposed in the middle of the time window. Residues were managed based on crop species exporting half (50 %) of the aboveground cereal straw and 80 % of the fodder maize and removing 20 % from the residues of all the other crop types (harvesting losses), including grain maize (Scarlat et al., 2019). Typical sowing crop densities were imposed based on Steduto et al. (2012).

The fertilisation amount for each crop is defined as the yearly mean dose designated for that crop within the most frequent succession of the simulation unit. Dose fractionation and fertilisation dates were established based on the crop type and the sowing date, total nitrogen amount, and mineral and organic repartition (see Supplement S2 for details). Organic fertilisers used in this study have a fixed C:N ratio of 25.

Irrigation was automatically supplied to the simulation units defined as "irrigable", based on the European agricultural area for the year 2016. An irrigable area is defined as an area equipped for irrigation that exceeds 5 % of the total utilised agricultural area (Eurostat, 2019b). This share represents 36 % of the simulation units and is mainly concentrated in the Mediterranean area; southern France and north-west France; the Netherlands; and some regions in Denmark, Germany and the UK. The irrigation volume was distributed automatically at the rate of 10 mm d^{-1} when the soil available water content was below 90 %. This means that non-irrigated crops potentially have access to irrigation water. Even if in the coming decades the global irrigated area is not expected to grow further due to water scarcity and limited land (Turrall et al., 2011), to account for a possible increase in the irrigable share moving towards 2100, a management scenario to observe the maximum potential irrigation water demand for today's crops grown in Europe was simulated and discussed. This management is evaluated over the century by the two scenarios *i_RCP4.5* and *i_RCP8.5* and provides access to irrigation water for the entire European agricultural area.

2.2.4 Grassland and livestock data

Grassland data considered permanent grassland and rainfed temporary grassland. Nitrogen fertiliser application for European grasslands in a 0.25° side resolution grid was estimated on the basis of regional and national statistics (Eurostat) and the CAPRI model (Leip et al., 2008). Data were generated combining fertilisation management and nitrogen doses, together with the number of mowing events, animal

loads, quantities of mineral fertilisers and/or organic nitrogen, and the fraction of legumes. Mowing dates were defined from temperature using thermal sums (500 degree days from 1 January) with a base of 5°C . Cutting was performed once such thermal sums were obtained. Fertilisation events occurred 3 d after mowing. Grazing started 30 d after the first mowing event and ended either at the end of the year or at the first freezing period of 5 consecutive days. Livestock were represented in the model only by cattle. Livestock densities (LSU ha^{-1} , where LSU denotes livestock units) were obtained from 0.05° side regional statistics (Wint and Robinson, 2007), multiplying the total number of animals per surface unit to 0.8, 0.1 and 0.1 for cattle, sheep and goats, respectively. Finally, LSU density distribution was aggregated to the 0.25° side grid. As for cutting and fertilisation, if no thermal sums were reached, then no events were performed. Biomass production is considered the sum of the grazer intake and the cut biomass. For each simulation unit, livestock is only fed by grass (i.e. no external feed is considered). If the amount of daily aboveground biomass is not sufficient for grazing animals, animals are moved from the pasture. In this study we simulate livestock as they contribute to N cycling and thus are an important source of nitrogen in grassland, although we do not discuss here their production.

2.2.5 Model spin-up and computation

CERES-EGC and PaSim were first initialised with the soil C content taken from the ESDB for the year 2013, along with the other chemical and physical soil parameters. Then, for croplands, an equilibrium was set through a spin-up run using the weather period from 1951–1977, assuming that the cultivated area during this period was likely to have been continuously cultivated with the same crop successions. Equilibrium was reached before 1971 for all the pixels with an estimation error lower than 0.1 % of the relative variation in the soil C balance in 5 years. For grasslands, we first let the simulation drift for each pixel from 1840 based on HadGEM2-ES weather data. Subsequently, transformation rules were applied to move from past towards current management practices; i.e. from 1901–1950, a low intensification management level with no mineral fertilisation and cut at 900 degree days was applied. From 1951–2010, there was a gradual management intensification up to achieving the target levels (linear increase in quantities, progressive earlier shift in the cutting date). In this period, mineral nitrogen fertilisation was applied, starting with a low level in 1951. Finally, from 2010–2099, constant management according to the protocol come into effect.

A total of 86 724 runs divided into two land uses (8861 units for arable, with two climate scenarios, two crop rotations and two irrigation scenarios, and 7918 units for grasslands, with two climate scenarios) were simulated on a dedicated server.

Finally, simulations from cropland and grassland were merged by reporting outputs to the corresponding share of arable and permanent grasslands into each simulation unit. These shares were provided by the CORINE Land Cover inventory for the year 2018.

2.3 Greenhouse gas exchange and balance

To assess the net greenhouse gas exchange (NGHGE) of the agro-ecosystems investigated, the contribution of the biogenic GHGs (CO_2 , N_2O , CH_4) is combined and normalised to grams of CO_2 equivalent ($\text{g CO}_2 \text{ eq.}$) by using the relative global warming potential (γ_{gas}) at the 100-year time horizon (298 for N_2O , 25 for CH_4 and 1 for CO_2 ; IPCC, 2018), following the approach presented by Soussana et al. (2007).

$$\text{NGHGE} = \text{NEP} + \gamma_{\text{N}_2\text{O}} F_{\text{N}_2\text{O}} + \gamma_{\text{CH}_4} F_{\text{CH}_4} \quad (1)$$

The net ecosystem production (NEP) is the amount of organic C available for net ecosystem C storage, export or loss in an ecosystem, in terms of CO_2 . NEP represents the difference between the gross primary production – or photosynthesis – and the ecosystem respiration, which is the sum of the autotrophic respiration and heterotrophic respiration (HR); ruminant respiration from grasslands ecosystems is not accounted for in the HR term. Conventionally, a negative value of NEP indicates an uptake of CO_2 by the system, whereas a positive value is a release towards the atmosphere.

The annual net greenhouse gas balance (NGB) is calculated on the basis of Ammann et al. (2020) by including the export of C by harvested biomass (crop yield, mowing and animal intake), the export as crop residues and the import of C by manure (organic fertilisers and the excreta from grazers).

$$\text{NGB} = \text{NGHGE} + F_{\text{C-harvest}} + F_{\text{C-residues}} - F_{\text{C-manure}} \quad (2)$$

Since livestock do not graze throughout the whole year, their contribution to the carbon balance is represented by the intake of biomass, enteric fermentation (CH_4) and C in excreta. Carbon emissions from farm operations (i.e. tractor emissions), erosion and leaching processes, fire, or off-farm emissions (i.e. fertiliser manufacture, barns) are not included in the C budget; the effects of volatile organic compounds and CH_4 emissions from manure and from soil are considered negligible as well. Moreover, the C exported from animal production (body mass increase and milk production) is neglected in NGB calculation (e.g. Chang et al., 2015).

3 Results

3.1 Cropland and grassland production

3.1.1 Model validation

Simulated crop yields during the historical period ranged between 1.4 and 44.8 t ha^{-1} (at standard humidity) and were in good agreement with EU statistics reported in the Eurostat database (Eurostat, 2020) for the time span 1978–2004 (Fig. 1a; the time span considered represents the original crop rotation data and complies with the beginning of the climate scenarios). Root mean square error (RMSE) was equal to 2.24 t ha^{-1} and mean absolute error (MAE) to 1.32 t ha^{-1} , and the modelling efficiency (Nash and Sutcliffe, E) scored 0.96. Simulations with CERES-EGC overestimated the yields for grain maize, wheat, rye, oat, soybean and sunflowers. Potato, pulses, rapeseed, fodder maize, barley and sugar beet were slightly underestimated. The relative RMSE (RRMSE) for each crop, individually, ranged from 12.8 % to 38.6 % (Table S3 in the Supplement). Furthermore, reducing the simulation period to 1994–2004 to limit the effect of the crop annual genetic gain on measured data, the statistics above described were not significantly modified (data not reported). The comparison between simulated and Eurostat statistics at the country level (NUTS0) for the period 1978–2004 gave fitting results ($R^2 = 0.92$, $p < 0.01$; $\text{RMSE} = 5.58 \text{ t ha}^{-1}$; $\text{MAE} = 3.18 \text{ t ha}^{-1}$; $E = 0.84$) shown in Fig. S2.

Representative data for grassland production are still scarce at the EU level. Smit et al. (2008) computed the production of permanent grassland (pastures and meadows) across Europe based on national and international statistics for the period 1995–2004. The productivity simulated with PaSim (Fig. 1b) and aggregated to the NUTS2 level (257 regions in this study) showed a significant positive correlation ($R^2 = 0.68$, $p < 0.05$) with the statistics reported by Smit et al. (2008), following the environmental stratification of Europe (Metzger et al., 2005). Compared to these statistics, PaSim scored a RMSE of $2.37 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ (where DM denotes dry matter), a MAE of $2.04 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ and a negative E (-0.34). Simulated productivity was generally overestimated in the Mediterranean area (+55 %; representing 16 % of the surface) and eastern Europe (+20 %; representing 25 % of the surface). The overestimation in these areas is also verified by other modelling interpretations (Van Oijen et al., 2014; Chang et al., 2015, 2017; Blanke et al., 2018) and is due to the gap between potential (maximum) simulated productivity and real harvest data. A slight underestimation of the simulated production was recorded for the Atlantic North zone (-15 %; representing 8 % of the surface). Finally, livestock density and distribution were in line with the Eurostat findings at the country scale for the period 1995–2004, ranging from 0 to 1.35 LSU ha^{-1} (mean 0.34 LSU ha^{-1}). Livestock densities were higher in Belgium,

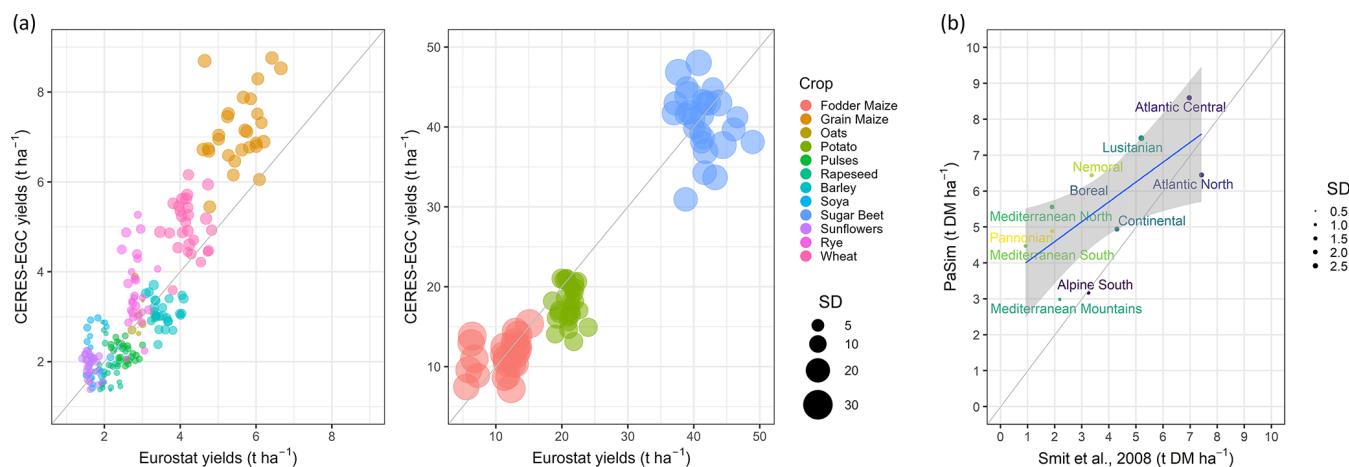


Figure 1. (a) Simulated crop yields compared with Eurostat statistics in the period 1978–2004. Each point represents the yearly yield over the EU for each crop; yields are reported as standard humidity. (b) Grassland production compared to Smit et al. (2008) for the period 1995–2004. Point size represents the standard deviation (SD) of the simulated production.

the Netherlands, Denmark and Ireland and in some regions of Germany, France, Italy and Spain, as also reported by Lesschen et al. (2011). Further details regarding grassland productivity are reported in the Supplement S3.

3.1.2 Effects of climate change scenarios on productive systems

Our results showed increasing cropland and grassland production in Europe during the historical scenarios (Fig. 2). Production was positively correlated with the increasing air temperatures over this period. The Mann–Kendall test highlighted a positive linear increase ($p < 0.01$) in the mean annual maximum air temperature ($0.05 \text{ }^\circ\text{C yr}^{-1}$) and minimum air temperature ($0.04 \text{ }^\circ\text{C yr}^{-1}$), as well as in solar radiation ($0.02 \text{ MJ m}^{-2} \text{ yr}^{-1}$).

Crop production in Europe assumed a positive yearly increase during the historical period ($18.1 \text{ kg DM ha yr}^{-1}$; Fig. 2a), which persisted until 2020, reaching 4.6 t DM ha^{-1} (average 2005–2020). Crop production rose in the first half of the century for both climatic scenarios ($+5 \%$, or $+0.2 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ compared to the average of the historical period; Table 1), even if the rate of increase slowed over time, especially from 2020–2050. In the second part of the century, crop production remained stable for the RCP4.5 scenario ($+2.2 \%$ compared to the average of the historical period), while a reduction of -6.1% is forecasted for the RCP8.5 scenario; this decline reached -13% at the end of the century (period 2080–2099). The extension of irrigation to all European croplands promotes crop production, which gained $+10 \%$ in the first half of the century for both $i_RCP4.5$ and $i_RCP8.5$. In the second part of the century crop production was sustained at the same value only for RCP4.5, while irrigation was able to mitigate the projected

yield decline forecasted for the RCP8.5 scenario ($+2 \%$ compared to the historical period).

Crop production showed a clear trend over latitudes and over time. During the historical period, crops were more productive in low latitudes ($< 45^\circ$; mean yield of $6.87 \text{ t DM ha}^{-1} \text{ yr}^{-1}$) than in mid-latitudes (45 to 55°) (-25% , $p > 0.05$, or $5.15 \text{ t DM ha}^{-1} \text{ yr}^{-1}$) and higher latitudes ($> 55^\circ$) (-46% , $p > 0.05$, or $3.69 \text{ t DM ha}^{-1} \text{ yr}^{-1}$). These gaps were reduced during the climate scenarios (see Table S1 in Supplement). At low latitudes, yields were slightly lower than the historical period in the first half of the century (-2%), undergoing severe reductions towards the end of the century (-4% and -11% for RCP4.5 and RCP8.5, respectively). Moving to mid-latitudes, crop production increased in the first part of the century for both climatic scenarios ($+5 \%$), remained at about the same level for RCP4.5 in the second part of the century and decreased (-8%) for RCP8.5. High latitudes were characterised by a general increase in production towards the end of the century (from $+8 \%$ to $+14 \%$) for both climate scenarios.

The yields of the two most cultivated crops in terms of area in Europe, grain maize and winter soft wheat, were not negatively affected by climate perturbations in the first half of the century with the RCP4.5 scenario, while a slight increase is expected in the RCP8.5 scenario for grain maize ($+2 \%$; average 2030–2049) and a decrease for winter soft wheat (-4%). Drastic reductions are projected for grain maize yield at the end of the century for both climate scenarios (-5% in RCP4.5 and -19% for the RCP8.5, average 2080–2099). Conversely, production is expected to increase for winter soft wheat for RCP4.5 (up to $+8 \%$), and a slight decline (-1%) is forecasted for RCP8.5 (Fig. S3a, b). The adoption of irrigation for all European croplands increased the productivity of grain maize compared to the irrigable scenario ($+8 \%$ towards the mid-century for both irrigated sce-

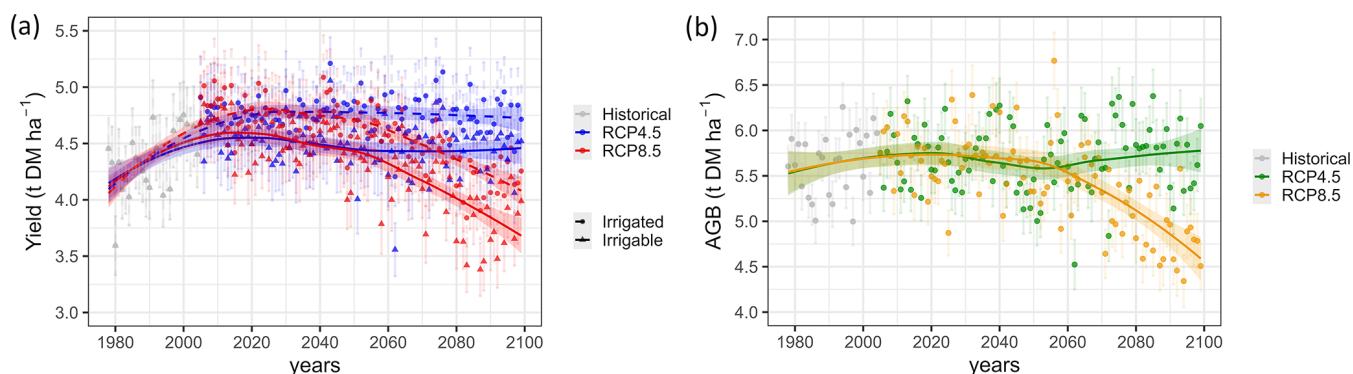


Figure 2. (a) Crop yield trends in Europe from 1978 to 2099 with the two climatic scenarios RCP4.5 and RCP8.5 and two irrigation conditions following the irrigable agricultural area in Europe or extending the irrigation to all the arable lands (i_RCP4.5 and i_RCP8.5); all crops confounded. (b) Grassland yield reported as aboveground biomass (AGB), which is the sum of biomass mowed and ruminant intake.

Table 1. Emissions of N₂O and CH₄, the net ecosystem production (NEP; for the sign convention, negative values represent a stock of carbon), and productivity from grassland and croplands. Between brackets is the standard deviation.

Scenario and period		N ₂ O		CH ₄		NEP		Productivity*	
		Mean kg N ha ⁻¹ yr ⁻¹	Rate g N ha ⁻¹ yr ⁻¹	Mean kg C ha ⁻¹ yr ⁻¹	Rate g C ha ⁻¹ yr ⁻¹	Mean kg C ha ⁻¹ yr ⁻¹	Rate g C ha ⁻¹ yr ⁻¹	Mean kg DM ha ⁻¹ yr ⁻¹	Rate g DM ha ⁻¹ yr ⁻¹
Period 1978–2004									
Historical	Grassland	0.81 (0.1)	2.4	6.71 (0.4)	15.6	−622 (62)	−774	5635 (250)	9202
	Cropland	1.44 (0.2)	2.2			−3403 (214)	251	4359 (297)	18 107
Period 2005–2049									
RCP4.5	Grassland	0.92 (0.1)	3.6	6.80 (0.4)	−6.2	−524 (65)	432	5697 (271)	−3457
	Cropland	1.52 (0.2)	1.3			−3505 (217)	−3268	4578 (313)	−2598
i_RCP4.5	Cropland	1.55 (0.2)	1.7			−3703 (225)	−4650	4815 (322)	393
RCP8.5	Grassland	0.92 (0.1)	3.4	6.76 (0.4)	−7.2	−519 (66)	995	5713 (274)	−1524
	Cropland	1.57 (0.2)	2.9			−3542 (215)	1441	4600 (314)	−7723
i_RCP8.5	Cropland	1.59 (0.2)	3.0			−3740 (223)	−111	4832 (322)	−5167
Period 2050–2099									
RCP4.5	Grassland	1.05 (0.1)	0.5	6.71 (0.5)	4.3	−526(71)	149	5695 (288)	5411
	Cropland	1.66 (0.3)	3.6			−3472 (211)	−1661	4454 (304)	1567
i_RCP4.5	Cropland	1.64 (0.2)	2.4			−3713 (222)	−455	4775 (314)	−471
RCP8.5	Grassland	1.21 (0.1)	7.4	6.13 (0.4)	−23.7	−298 (65)	6407	5201 (285)	−21 777
	Cropland	1.93 (0.3)	10.0			−3293 (210)	9838	4094 (277)	−16 171
i_RCP8.5	Cropland	1.96 (0.3)	11.7			−3529 (221)	9488	4445 (290)	−13 988

* Yield for croplands and the sum of harvested biomass and animal intake for grasslands.

narios; +13 % and +16 % towards the end of the century for i_RCP4.5 and i_RCP8.5, respectively). On the other hand, small yield increases are expected with the irrigation scenario for winter soft wheat.

Figure 3 shows the length of the growing season for grain maize and winter soft wheat, underlining a consistent reduction during both climatic scenarios. The crop growing cycle

considers that sowing dates were modulated according to climatic conditions. Compared to the historical period, in the middle of the century there was a general reduction in the growing season of −8 d for grain maize (−12, −5 and +9 d for low, middle and high latitudes, respectively) and −20 d for winter soft wheat (−20, −19 and −6 d for low, middle and high latitudes, respectively). This trend remained con-

stant for the RCP4.5 scenario approaching 2100, whereas it worsened for RCP8.5, with averaged reductions of -27 and -36 d for grain maize and winter wheat, respectively. Severe reductions are expected at middle and low latitudes for grain maize (-34 and -24 d) and at middle and high latitudes for winter soft wheat (-49 and -38 d). The length of the growing cycle for all the simulated crops, except for potato and sugar beet, was reduced by 12 d in the middle of the century and by 19 d in the second part of the century (Fig. S4). Conversely, potato and sugar beet showed an extension of the length of the cropping cycle over time in both climate scenarios, especially towards the end of the century.

Considering the mild climate projections, positive yield increases from $+4\%$ to $+20\%$ are expected for durum and soft wheat, soybean, rye, and spring wheat for low latitudes and towards the end of the century. On the other hand, grain and fodder maize, potato, barley, sugar beet, pulses, and oat are affected by substantial reductions (from -1% to -44%). The extension of irrigation was able to increase yields for the more water-demanding crops (grain and fodder maize, sunflowers, sugar beet, and potato) with increases of more than $+10\%$. At mid-latitudes strong reductions, in the range of -2% to -17% , are expected for a large part of the main European crops (durum and soft wheat, potato, rapeseed, barley, soybean, spring soft wheat, sugar beet, and sunflowers), whereas fodder maize and winter rye were projected to increase ($+30\%$ and $+9\%$, respectively). High latitudes displayed reductions in yields for pulses and barley (-22% and -11% , respectively) and an increase ($+7\%$ up to $+100\%$ and over) for rapeseed, sugar beet, potato, grain and fodder maize. The extension of irrigation to all European croplands will not cause discernible improvement for middle and high latitudes for *i*_RCP4.5, while a substantial reduction in yields is projected for all the crops in *i*_RCP8.5.

With the irrigation scenario, irrigation was applied to 93 % of all the simulation units, doubling the volumes needed to fulfil the evapotranspiration deficit (160 mm yr^{-1} in the first half of the century) compared to the historical period (82 mm yr^{-1}). Then, water volumes needed in the second half of the century were less for *i*_RCP4.5 (114 mm yr^{-1}) and greater for *i*_RCP8.5 (176 mm yr^{-1}). Compared to the scenario with the actual irrigable surface, these volumes increased by more than 2 and 5 times at middle and high latitudes and only by $+30\%$ at low latitudes, indicating that the extension of irrigable areas became an essential to guarantee adequate levels of crop production, especially in the Mediterranean regions.

Grassland productivity showed a trend over time similar to that of croplands (Fig. 2b; Table 1). Compared to the historical period, grassland productivity slightly increased until 2020 and declined towards the middle of the century, with an average production of 5.6 t DM ha^{-1} (average 2030–2049). Biomass productivity is maintained during the progress of the RCP4.5 scenario ($+1\%$, or $+0.1\text{ t DM ha}^{-1}\text{ yr}^{-1}$), whereas an averaged reduction of about 0.45 t DM ha^{-1}

(-7.7% compared to the historical period) is expected for the RCP8.5 scenario in the second part of the century. During the historical period, grassland productivity at low latitudes was $4.58\text{ t DM ha}^{-1}\text{ yr}^{-1}$ and resulted in about 30 % lower levels compared to both middle and high latitudes, with higher production concentrated in north-west Europe. A substantial increase in production was observed towards 2050 for both low latitudes ($+6\%$ for RCP4.5 and $+7\%$ for RCP8.5) and high latitudes ($+12\%$ and $+15\%$ for RCP4.5 and RCP8.5, respectively; Fig. S3c and Table S1 in the Supplement). Moving to the end of the century, grass production increased further compared to the historical period, especially for RCP4.5 ($+11\%$ and $+22\%$ for low and high latitudes, respectively), while a less marked increase is expected for RCP8.5 ($+1\%$ and $+13\%$ for low and high latitudes, respectively). At central European latitudes, characterised by a higher livestock density than low and high latitudes ($+42\%$ and $+13\%$, respectively), productivity was reduced by 5 % in the first part of the century. Towards the end of the century, this reduction remains at the same level for RCP4.5, while it was more pronounced for RCP8.5 (-24%).

3.2 GHG emissions

3.2.1 N_2O emissions

N_2O emissions for croplands increased sharply for both climate scenarios during the century (Fig. 4a). During the historical period, a constant growth of the emissions is observed at the rate of $2.2\text{ g N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$, with a mean value of $1.44\text{ kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ (Table 1). This rate decreased to $1.3\text{ g N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ in the first half of the century for the RCP4.5 scenario, while a rise to $2.9\text{ g N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ is forecasted for the RCP8.5 scenario. In the second part of the century, the rate of N_2O emissions nearly tripled for both climate scenarios compared to the emission in the first half of the century. RCP4.5 reached a value of $1.69\text{ kg N-N}_2\text{O ha}^{-1}$ towards the end of the century (average 2080–2099), whereas the RCP8.5 scenario reached $2.09\text{ kg N-N}_2\text{O ha}^{-1}$ in the same period. The extension of irrigation to all European croplands amplified the emission rates in the first half of the century for both *i*_RCP4.5 and *i*_RCP8.5, increasing the emissions of 0.03 and 0.02 $\text{kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$, respectively, compared with the irrigable scenario. In the second part of the century, emission rates decreased for *i*_RCP4.5 ($-0.02\text{ kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$) compared with the irrigable scenario, whereas they continued to grow ($+0.03\text{ kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$) for *i*_RCP8.5. Interestingly, the interannual variance of N_2O emissions increased from the historical period to the first half of the century ($+0.02\text{ kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$) and continued for the second part of the century ($+0.08$ and $+0.14\text{ kg N-N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ for RCP4.5 and RCP8.5, respectively), while the extension of irrigation contributes to reducing this variance in the sec-

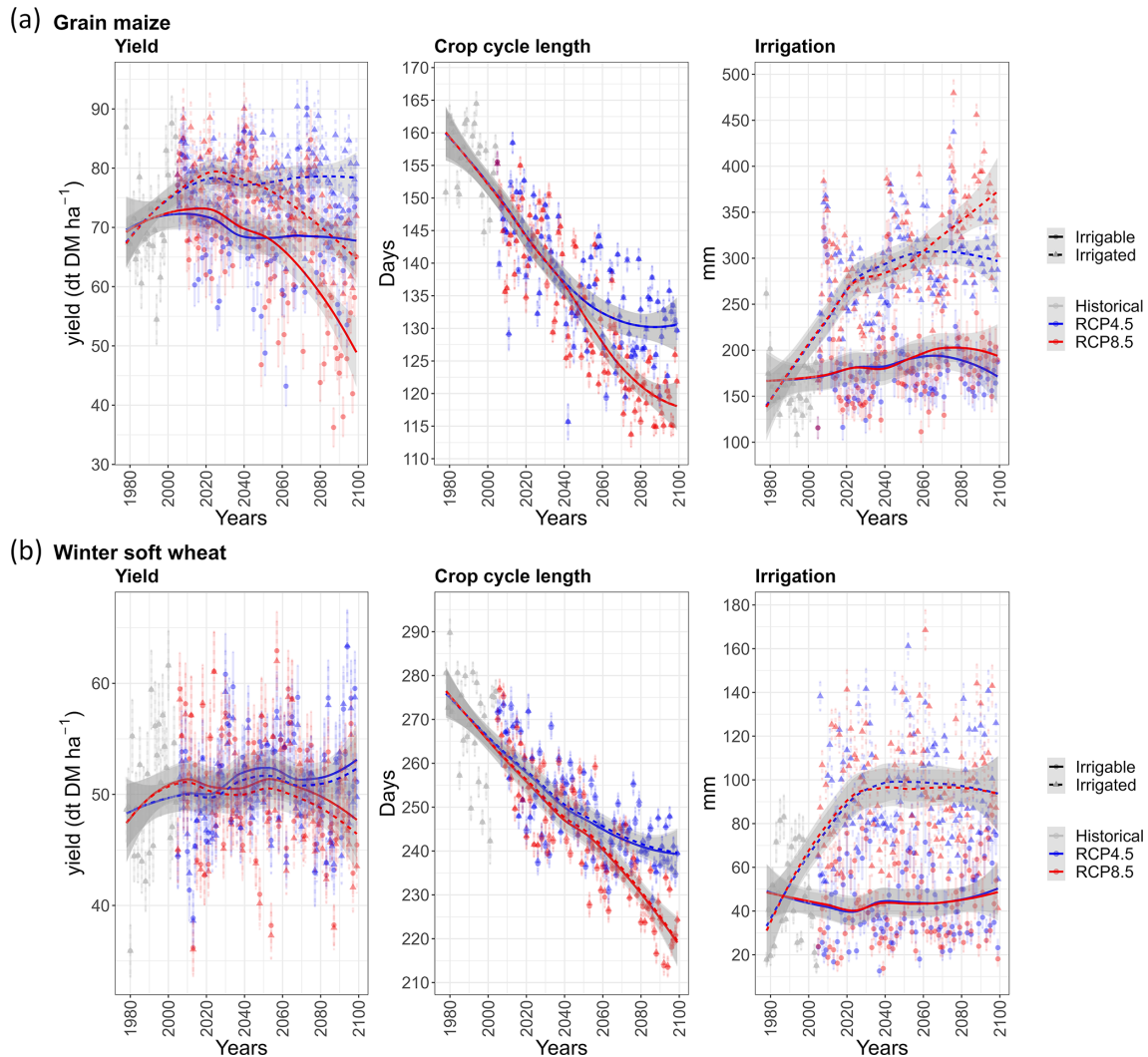


Figure 3. Yield, length of the cropping season and irrigation needed over the cropping cycle for grain maize (a) and winter soft wheat (b) in the two climatic scenarios RCP4.5 and RCP8.5; the figure shows results for the irrigable agricultural area in Europe and the extension of the irrigation to all the European arable area (scenarios *i_RCP4.5* and *i_RCP8.5*).

ond part of the century for both *i_RCP4.5* and *i_RCP8.5* scenarios (-0.05 and -0.03 kg N-N₂O ha⁻¹ yr⁻¹).

N₂O emissions from grasslands showed a similar trend over the years to that for croplands (Fig. 4b), characterised by lower rates. During the historical period, the emissions increased at a rate of 2.4 g N-N₂O ha⁻¹ yr⁻¹, reaching a mean value of 0.81 kg N-N₂O ha⁻¹ yr⁻¹ (Table 1). This rate rose to about 3.5 g N-N₂O ha⁻¹ yr⁻¹ during the first half of the century; afterwards the two different climate scenarios showed different trends. RCP4.5 was characterised by a significant reduction in the emission rate to 0.5 g N-N₂O ha⁻¹ yr⁻¹, while the rate tripled for RCP8.5, which reached a mean emission of 1.32 kg N-N₂O ha⁻¹ yr⁻¹ at the end of the century (average 2080–2099). A total emission of 1.05 kg N-N₂O ha⁻¹ yr⁻¹ is expected for RCP4.5 in the same integration period.

Total N₂O emissions from croplands and grasslands were reported for the surface allocated for arable crops and permanent grasslands for each simulation unit (Fig. 5). Emissions ranged between 0 and 2.5 kg N ha⁻¹ yr⁻¹ during the historical period and were concentrated in hotspots, such as northern Italy, north-east Germany and Poland, southern England, Bulgaria, eastern Romania, the Scandinavian Peninsula, and north-western Spain and Portugal. During the climatic projections, a general worsening of N₂O emissions is observed, reaching up to and often over 1 kg N ha⁻¹ yr⁻¹, especially towards the end of the century and for the strongest climatic scenario. An average emission of 1.02 kg N-N₂O ha⁻¹ yr⁻¹ (corresponding to 0.163 Mt N-N₂O yr⁻¹) was emitted during the historical period. This amount rose to 1.06 and 1.08 kg N-N₂O ha⁻¹ yr⁻¹ (0.166 and 0.170 Mt N-N₂O yr⁻¹) in the first half of the century for RCP4.5 and RCP8.5, respectively. In

the second half of the century total N₂O emissions assumed a further increase to 1.11 and 1.13 kg N-N₂O ha⁻¹ yr⁻¹ (0.169 and 0.174 Mt N-N₂O yr⁻¹) for RCP4.5 and RCP8.5, respectively. The representation of separate emissions of N₂O from croplands and grasslands in Europe is shown in Fig. S5a and b.

The N₂O emission factor (EF), defined as the ratio between the N emitted as N₂O from croplands and grasslands and the N introduced into the system (not including the N added by animal excretion, crop residue, atmospheric deposition, soil mineralisation and fixation), had the same trend as described for N₂O over time. During the historical period the averaged EF for croplands was 1.88 ± 0.32 %, while the EF for grasslands was 1.99 ± 0.16 %; see Fig. S6a and b.

Combining cropland and grassland emissions over each simulation unit, the resulting EF was 1.82 ± 0.07 % during the historical period, which rose to 1.90 ± 0.09 % for RCP4.5 and 1.94 ± 0.09 % for RCP8.5 in the first half of the century. The EF was 2.02 ± 0.11 % and 2.05 ± 0.11 % for RCP4.5 and RCP8.5, respectively, in the second part of the century. The spatial distribution of EF values at the NUTS2 scale, as shown in Fig. 6, varies from 0.1 % to over 5 % in the historical period, assuming variations of ± 1 % in RCP4.5 and up to ± 10 % in RCP8.5. The European hotspots were the same described for the N₂O emissions.

The specific EF for the simulated crops, calculated in the period from sowing (including pre-sowing management) to the sowing of the next crop in a succession (excluding pre-sowing management), ranged from 0.9 % to 3.4 % in the historical period and is shown in Fig. 7. EFs towards the middle and the end of the century rose for all the crops, with a greater impact for the RCP8.5 scenario, except for winter soft wheat, which exhibited lower EF values over the century, and soybeans, which presented a low EF at the end of the century for RCP8.5 compared to the mild scenario. Figure 7 also shows the EF for N₂O for grasslands, which assumed an increasing behaviour over the course of the century and according to the strength of climate scenarios.

3.2.2 CH₄ emissions

The emissions of CH₄ from enteric fermentation are shown in Fig. 8. During the historical period, a mean emission of 6.71 kg C-CH₄ ha⁻¹ yr⁻¹ was observed, with a rate of 15.6 g C-CH₄ ha⁻¹ yr⁻¹ (Table 1). The emission rate halved in the first part of the century, increased slightly in the second part of the century for RCP4.5 (4.3 g C-CH₄ ha⁻¹ yr⁻¹) and strongly decreased for the RCP8.5 scenario (-23.7 g C-CH₄ ha⁻¹ yr⁻¹). Emissions towards the end of the year were 6.73 kg C-CH₄ ha⁻¹ yr⁻¹ for RCP4.5 (average 2080–2099) and 5.74 kg C-CH₄ ha⁻¹ yr⁻¹ for RCP8.5 in the same period. The averaged CH₄ emissions per head ranged from 2.99 kg CH₄ per head per year in the historical period to 3.03 and 3.01 kg CH₄ per head per year in the first half of the century for RCP4.5 and RCP8.5, respectively. In the sec-

ond half of the century a reduction to 2.98 and 2.73 kg CH₄ per head per year is expected for RCP4.5 and RCP8.5, respectively. The spatial distribution of CH₄ emissions at the NUTS2 scale (Fig. 9) ranged from 0 to over 20 kg C-CH₄ ha⁻¹ yr⁻¹ in the historical period and was concentrated in the north-western part of Europe. During the climate projections, methane emissions assumed wide variations, in the range of ± 11.5 kg C-CH₄ ha⁻¹ yr⁻¹, with increases mostly in northern Europe.

3.2.3 Carbon fluxes

Results are presented with the sign convention indicating CO₂ accumulation as negative, and CO₂ losses as positive. Net ecosystem production (NEP) for European croplands showed an accumulation of CO₂ in the historical period (-3403 kg C-CO₂ ha⁻¹ yr⁻¹) and a clear intensification until 2050 (about +3 %). Rates were contrasting for RCP4.5, with -3.27 kg C-CO₂ ha⁻² yr⁻¹, and for RCP8.5, with +1.44 kg C-CO₂ ha⁻² yr⁻¹ (Fig. 10a; Table 1). In the second part of the century, a net divergence is expected, with CO₂ accumulation for RCP4.5 (rate of -1.66 kg C-CO₂ ha⁻¹ yr⁻¹) and a marked decrease for RCP8.5 (rate of +9.84 kg C-CO₂ ha⁻¹ yr⁻¹). Extending the irrigation area over all European croplands, taking advantage of irrigation volumes according to crop needs and soil water status, produced a proportional increase in CO₂ accumulation in the climatic scenarios for both the first half of the century (+6 %, or about +236 kg C-CO₂ ha⁻¹ yr⁻¹) and the second half (+7 %, or about +321 kg C-CO₂ ha⁻¹ yr⁻¹). At low European latitudes and for the historical period, NEP for croplands was 4359 kg C-CO₂ ha⁻¹ yr⁻¹, higher than middle and high latitudes (-11 % and -50 %). NEP at low latitudes is expected to increase moving towards 2050 (+3 %) for both RCP4.5 and RCP8.5 (Fig. S7a; Table S1). This trend is inverted towards the end of the century for the RCP4.5 scenario (-1 %) and becomes more severe for RCP8.5 (-8 %). At central European latitudes there is an accumulation of CO₂ in the first part of the century for both climate scenarios (+9 %), which is maintained for RCP4.5 towards the end of the century and tends to be released (-3 %) for the RCP8.5 scenario.

Compared to central European latitudes, higher latitudes showed a tendency to store more CO₂ for the RCP4.5 scenario with respect to the historical period (+5 % in the middle of the century and +9 % at the end of the century), whereas a tendency to release CO₂ is forecasted for the RCP8.5 scenario, especially towards the end of the century (-5 %). The extension of irrigation to all European areas showed clear CO₂ losses for all latitudes.

NEP in grasslands indicated a clear trend towards CO₂ accumulation in the system during the historical period (-622 kg C-CO₂ ha⁻¹ yr⁻¹) with a rate of -0.77 kg C ha⁻¹ yr⁻¹ (Fig. 10b; Table 1). Approaching 2050 a slight imbalance and a tendency to release CO₂ are observed for both climate scenarios (around 100 kg C-

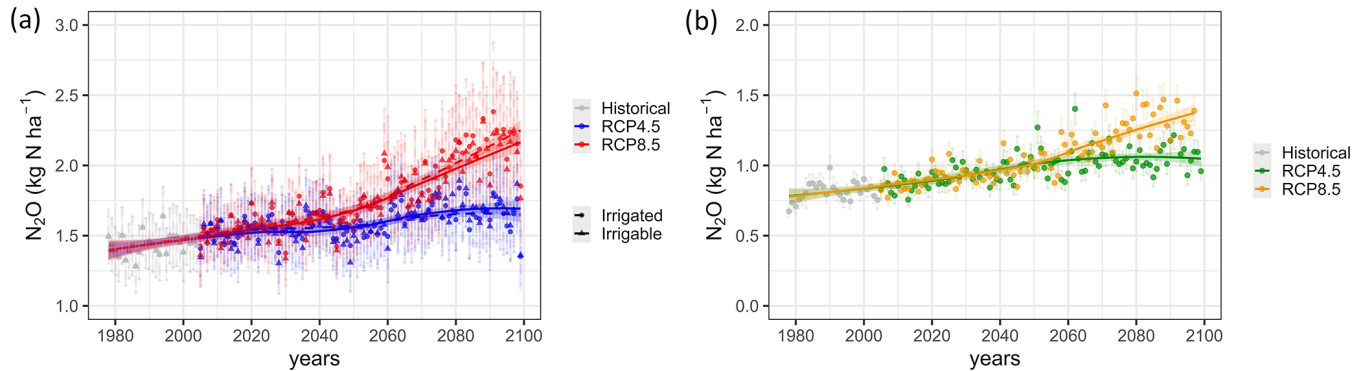


Figure 4. N₂O emissions (kg N ha⁻¹ yr⁻¹) for (a) croplands and (b) grassland with two climate change scenarios (RCP4.5 and RCP8.5). N₂O emissions for croplands consider two irrigation conditions, following the irrigable agricultural area in Europe or extending the irrigation to all the arable lands (i_RCP4.5 and i_RCP8.5).

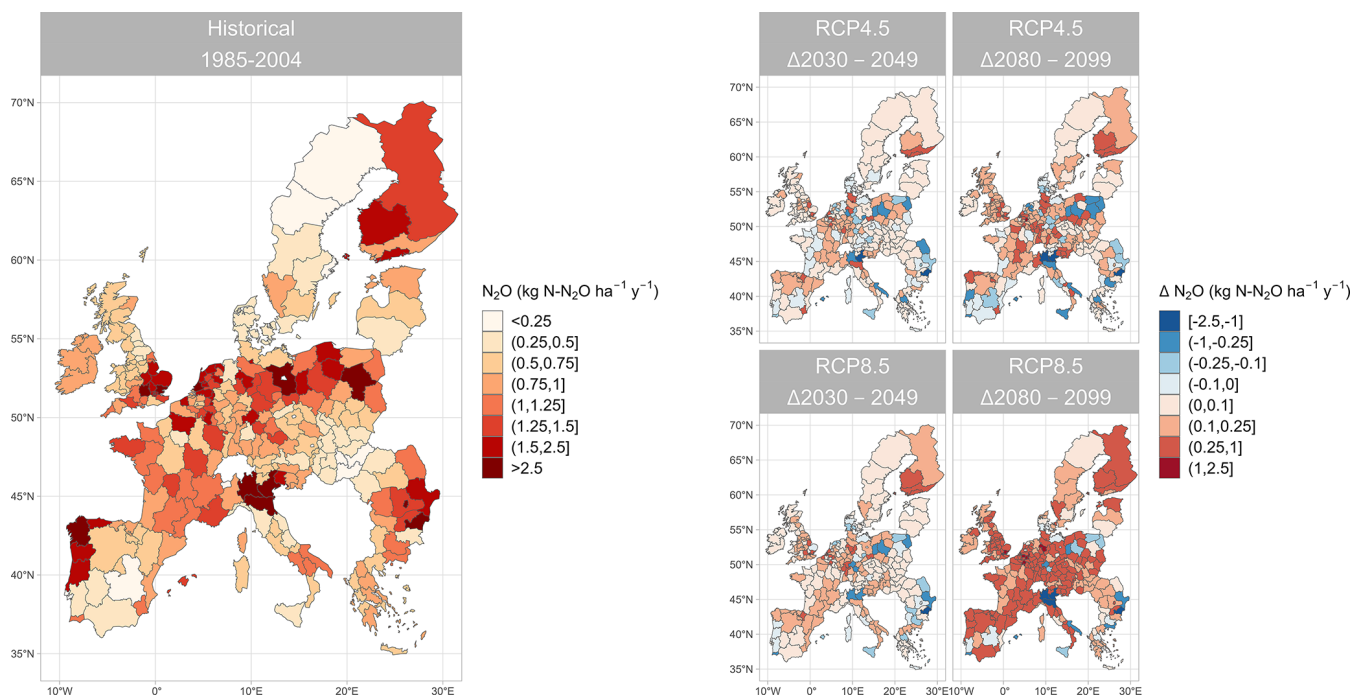


Figure 5. N₂O emissions for croplands and grasslands in European administrative regions (NUTS2). Emissions are reported for the historical period (1985–2004) and difference Δ from the middle (2030–2049) and the end (2080–2099) of the century for the two climatic scenarios RCP4.5 and RCP8.5. N₂O emissions are reported for cropland with the irrigable scenario (see the text).

CO₂ ha⁻¹ yr⁻¹). Approaching 2100, the amount of CO₂ potentially stored in the system is maintained for RCP4.5, while a clear release of CO₂ is forecasted for the scenario without adaptation to climate change (324 kg C-CO₂ ha⁻¹ yr⁻¹), projecting a potential loss of 50 % of the CO₂ stored annually in the historical period. A potential release of CO₂ was also projected for RCP4.5 for low latitudes, both in the middle (-7 %) and towards the end of the century (-16 %), compared to the historical period (-631 kg C-CO₂ ha⁻¹ yr⁻¹; Table S1). Higher decreases are forecasted for RCP8.5 for the lower latitudes, -13 % and -37 % in the first and the sec-

ond half of the century, respectively. Conversely, grasslands tend to stock more CO₂ in high latitudes during the historical period (-960 kg C-CO₂ ha⁻¹ yr⁻¹, double compared to low latitudes) and become a further CO₂ sink for the climate scenarios for the middle of the century (+2 %). For the second half of the century RCP4.5 increased the stock (+3 %), while RCP8.5 became negative (-31 %) towards the end of the century. The intermediate latitudes, corresponding to central Europe, displayed a strong susceptibility to CO₂ release in both climatic scenarios, ranging between -19 % and -31 % for RCP4.5 in the middle and at the end of the century, re-

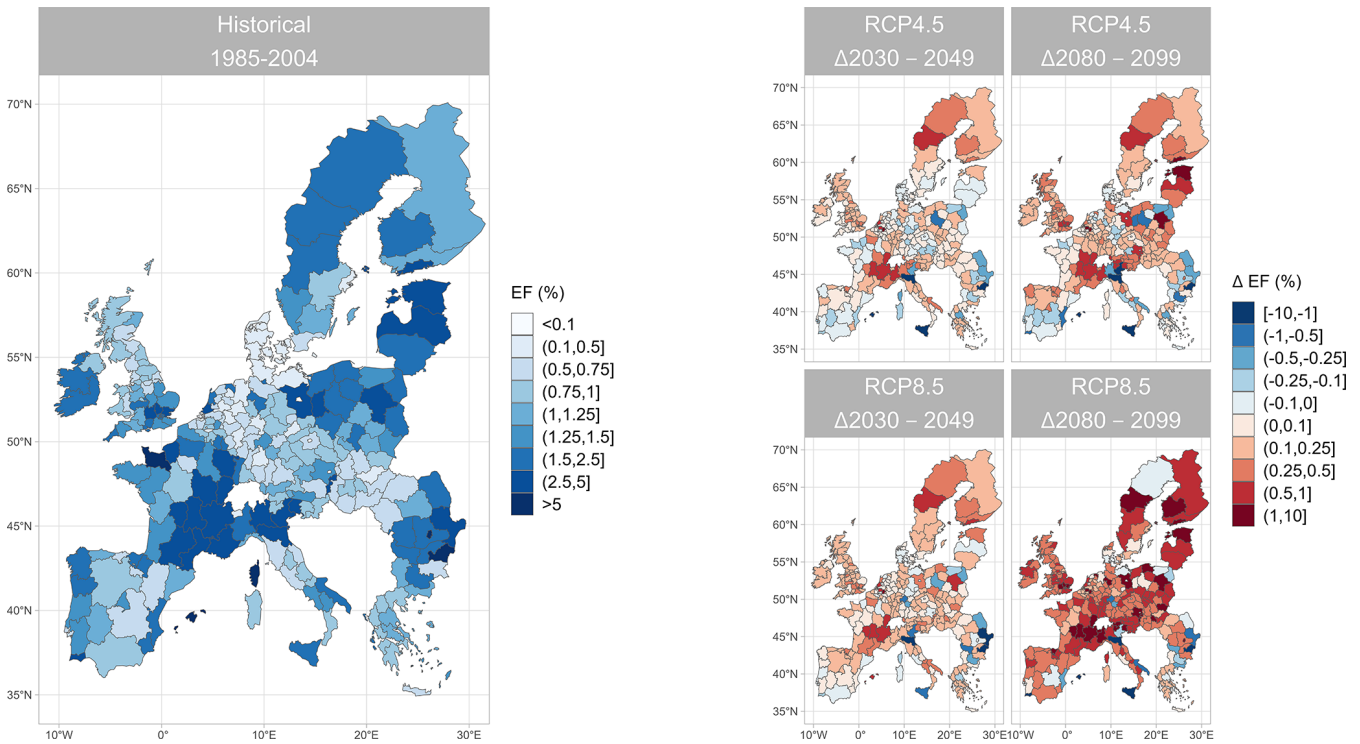


Figure 6. The N₂O emission factor (EF %) for croplands and grasslands in European administrative regions (NUTS2). The EF is reported for the historical period (1985–2004) and the difference Δ from the middle (2030–2049) and the end (2080–2099) of the century for the two climatic scenarios RCP4.5 and RCP8.5. The EF is calculated as the ratio between the N emitted as N₂O from croplands (irrigable scenario) and grasslands and the N introduced into the system as fertiliser (not including the N added by animal excretion, crop residue, atmospheric deposition, soil mineralisation and fixation).

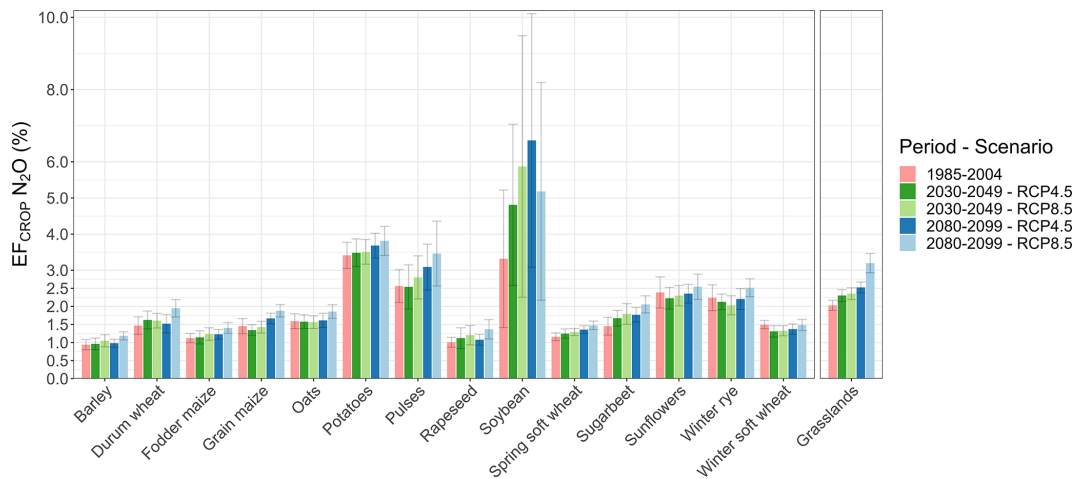


Figure 7. The emission factor (EF) for N₂O (%) for the different crops and grasslands for the historical period (1985–2004), towards the mid-century (2030–2049) and towards the end of the century (2080–2099), for the two climatic scenarios RCP4.5 and RCP8.5. The EF is the ratio between the N emitted as N₂O from crops and grasslands and the N applied as fertiliser.

spectively, and becoming more negative ($< -50\%$) for the RCP8.5 scenario (Fig. S7b).

NEP of the European cropland and grasslands system, obtained reporting emissions from the surface allocated to arable crops and permanent grasslands in each simulation

unit, is shown in Fig. 11. During the historical period, NEP varied between -7500 and $+200$ kg C-CO₂ ha⁻¹ yr⁻¹ within the European regions. Climate projections showed variation of up to ± 2800 kg C-CO₂ ha⁻¹ yr⁻¹ from the historical values, indicating a tendency to store less CO₂ in

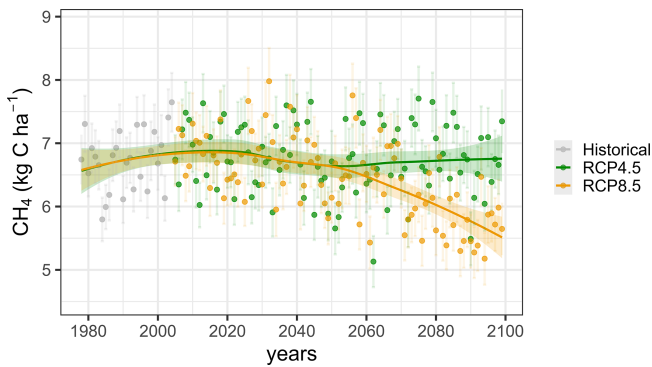


Figure 8. CH₄ emissions (kg C-CH₄ ha⁻¹ yr⁻¹) from enteric fermentation in grasslands with two climate change scenarios (RCP4.5 and RCP8.5).

the first half of the century, especially for the Mediterranean regions. CO₂ stock is further reduced in central European latitudes towards the end of the century for the RCP4.5 scenario and showed a strong reduction in all regions during RCP8.5. A total of -1241 Tg CO₂ eq. yr⁻¹ was stocked over Europe during the historical period (corresponding to -1865 kg C-CO₂ ha⁻¹ yr⁻¹). This amount rose in the first half of the century (-1232 Tg CO₂ eq. yr⁻¹ for RCP4.5 and -1244 Tg CO₂ eq. yr⁻¹ for RCP8.5) and further increased in the second half of the century for both climatic scenarios (-1176 Tg CO₂ eq. yr⁻¹ for RCP4.5 and -1073 Tg CO₂ eq. yr⁻¹ for RCP8.5) (Table 2).

The NGHGE still indicated a potential capacity of the European production systems to store -1155 ± 82 Tg CO₂ eq. yr⁻¹ as the average during the historical period. N₂O and CH₄ were able to offset the NEP by 6.2 % and 0.8 %, respectively. In the first half of the century, the NGHGE assumed a slight reduction for RCP4.5, indicating a potential C stock, whereas it remained substantially unvaried for RCP8.5. In the second part of the century the NGHGE increased for both RCP4.5 (-1087 ± 119 Tg CO₂ eq. yr⁻¹) and RCP8.5 (-997 ± 159 Tg CO₂ eq. yr⁻¹), indicating a decline in C accumulation. The extension of irrigation to all European agricultural surfaces highlights a further potential to stock C of about 3 % to 4 %, mainly due to the greater NEP values.

NGB indicated losses from European agricultural surfaces in the range of 2367 ± 107 Tg CO₂ eq. yr⁻¹ for the historical period (Table 2). Losses increased both in the first and the second half of the century and for both climate scenarios, being higher for RCP4.5 (-23 % and -26 % for the first and the second part of the century) than RCP8.5 (-19 % and -24 % for the first and the second part of the century). The extension of irrigation to the whole of Europe, which support productivity and biomass removals as well as the greenhouse gas emissions, increased the net C losses (-26 % and -22 % in the first part of the century for RCP4.5 and RCP8.5, re-

spectively, and -32 % for the second part of the century for both scenarios).

4 Discussion

4.1 Production

Results from this study confirmed that the effects of climate change, implying shifts in the temperature, precipitation and plant growing length among other factors, represent a serious drawback to plant production.

Air temperature. Our findings pointed out that the increase in air temperature during the climate scenarios was negatively correlated with productivity, leading to persistent reductions in biomass production in both grasslands and croplands. This behaviour is also confirmed by previous studies (e.g. Challinor et al., 2014; Lobell and Tebaldi, 2014; Olesen and Bindi, 2002; Zhang et al., 2017) and was more pronounced for the more pessimistic climate scenario (-0.15 and -0.29 t DM ha⁻¹ yr⁻¹ °C⁻¹ for RCP4.5 and RCP8.5, respectively, in the 2050–2099 period). Effects on crop yields ranged from +5 % to -11 % for every degree (°C) of rising air temperature from 2005–2100. This effect remained negative throughout most of the projected climate scenarios (-1 % and -5 %, for RCP4.5 and RCP8.5, respectively, in the period 2025–2099), as also reported by recent studies using modelling and multi-modelling approaches (e.g. Asseng et al., 2015; Bassu et al., 2014; Zhao et al., 2017; Yang et al., 2019). The extension of irrigable areas to all European croplands reduced the dependence of daily maximum and minimum air temperatures on crop production (Fig. S8). This leads to the assumption that even with access to water (no limitation on irrigation of the European cropping surfaces), biomass production will decline due to increasing air temperatures, as reported by Minoli et al. (2019). This can also be seen from the trend of biomass projections in Fig. 2, considering an increase in temperatures over time. Interestingly, grassland productivity assumed a less pronounced correlation with air temperature during climate scenarios compared to croplands (Fig. 12). The climatic scenario RCP8.5, characterised by a strong reduction in grassland production in the second half of the century, showed a significant negative correlation with minimum and maximum daily air temperatures ($r = -0.6$), whereas null correlation is observed for RCP4.5. Furthermore, crop yields were significantly correlated with minimum and maximum air temperatures ($r = 0.64$ and $r = 0.57$, respectively) compared to grasslands, which did not show such a dependence ($r = 0.1$ for both minimum and maximum air temperatures), highlighting a greater sensitivity of the CERES-EGC model to air temperatures compared to PaSim.

Precipitation. Results confirmed that rainfall has a significant positive effect for both crop production ($r = 0.41$ and 0.13 for RCP4.5 and RCP8.5, respectively) and grassland

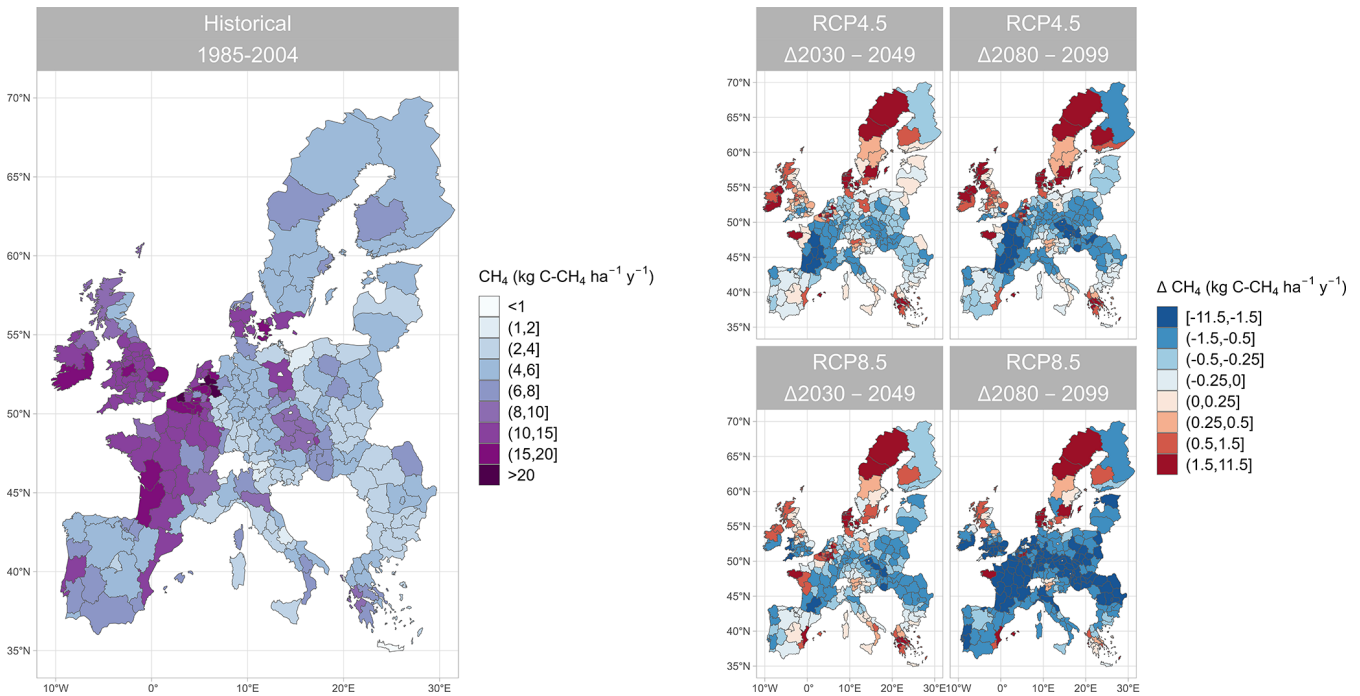


Figure 9. CH₄ emissions for grasslands in European administrative borders (NUTS2). Emissions are reported for the historical period (1985–2004) and difference Δ from the middle (2030–2049) and the end (2080–2099) of the century for the two climatic scenarios, RCP4.5 and RCP8.5.

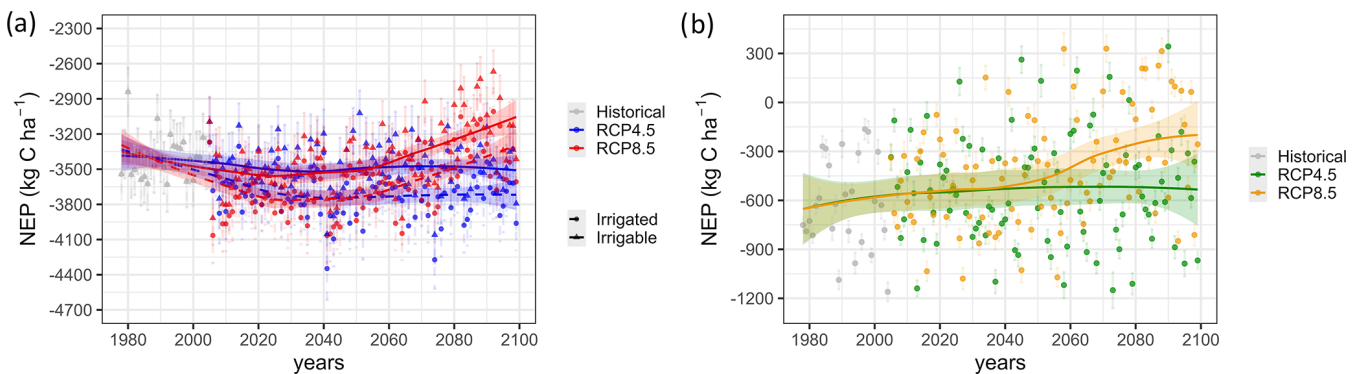


Figure 10. Net ecosystem production (NEP; kg C ha⁻¹) for croplands (a) and grasslands (b), with two climate change scenarios (RCP4.5 and RCP8.5). Croplands reported two irrigation conditions following the irrigable agricultural area in Europe or extending the irrigation to all the arable lands (scenarios *i_RCP4.5* and *i_RCP8.5*).

production ($r = 0.26$ in RCP8.5; r is null for RCP4.5). Compared to the historical period, a reduction in precipitation was predicted in the first half of the century for both scenarios (-2.1 mm yr⁻¹ for RCP4.5 and -0.74 mm yr⁻¹ for RCP8.5; $p < 0.01$), whereas in the second half of the century rainfall increases in RCP4.5 ($+1.2$ mm yr⁻¹; $p < 0.01$) and decreases in RCP8.5 (-0.59 mm yr⁻¹; $p < 0.01$). This effect was more pronounced for low latitudes (-1.2 and -2.3 mm yr⁻¹ for RCP4.5 and RCP8.5, respectively; $p < 0.01$) compared to high latitudes where the rainfall tends to increase during the century ($+0.26$ and $+0.1$ mm yr⁻¹ in RCP4.5 and RCP8.5,

respectively, with respect to the historical period; $p < 0.5$). This reduction in the cumulated precipitation will negatively affect the productivity with the climate change scenarios, as also confirmed by Hsu et al. (2012) for grasslands and by Olesen et al. (2011) for croplands.

Length of crop growing cycle. Apart from increases in temperature and reduction in precipitation, our simulation highlighted that crop yield is affected by the shortening of the length of the growing cycle, as confirmed by, for example, Bassu et al. (2014) and Tao and Zhang (2011). As detailed in our results, with a multi-model approach Bassu et al. (2014)

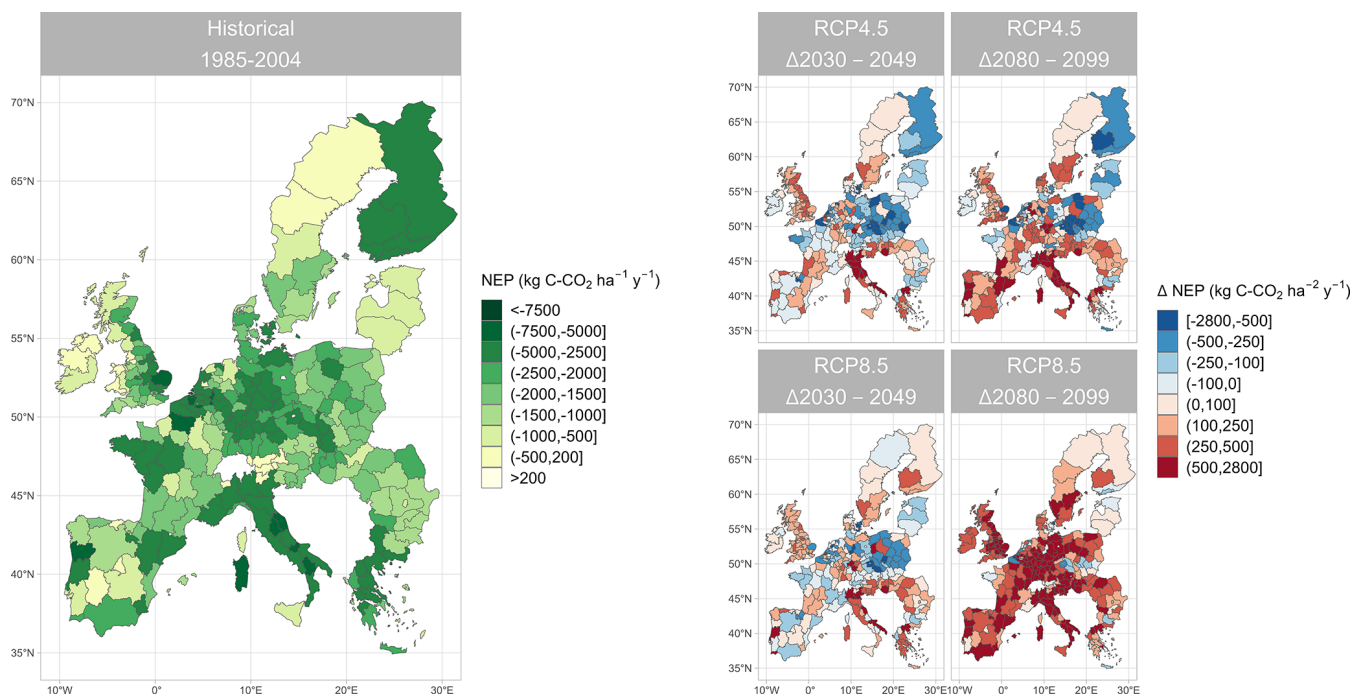


Figure 11. Net ecosystem production (NEP) for croplands and grasslands in European administrative borders (NUTS2). Results are reported for the historical period (1985–2004) and difference Δ from the middle (2030–2049) and the end (2080–2099) of the century for the two climatic scenarios RCP4.5 and RCP8.5. NEP for croplands is reported with the irrigable scenario (see the text).

Table 2. The net greenhouse gas exchange (NGHGE) and net greenhouse gas budget (NGB) in Europe during the historical and two climate change scenarios. The elements of the budget are reported: N_2O , CH_4 and the net ecosystem production (NEP; for the sign convention, negative values represent a stock of carbon). Results are in $\text{Tg CO}_2 \text{ eq. yr}^{-1}$. Between brackets is standard deviation.

Scenario and period	N_2O		CH_4		NEP		NGHGE		Harvest		Residues exported		Fertilisation and dung		NGB	
	$\text{Tg CO}_2 \text{ eq. yr}^{-1}$															
Period 1978–2004																
Historical	76.5	(3.4)	9.70	(0.9)	−1241	(82)	−1155	(82)	1186	(63)	296	(26)	90	(3.5)	236	(107)
Period 2005–2049																
RCP4.5	77.8	(3.6)	9.91	(0.9)	−1232	(113)	−1144	(113)	1229	(78)	297	(22)	92	(4.5)	290	(139)
i_RCP4.5	79.8	(3.1)	9.91	(0.9)	−1266	(103)	−1176	(103)	1258	(67)	307	(22)	92	(4.5)	298	(124)
RCP8.5	79.2	(4.5)	9.62	(0.9)	−1244	(104)	−1155	(104)	1230	(73)	299	(22)	91	(4.5)	282	(129)
i_RCP8.5	81.0	(4.5)	9.62	(0.9)	−1279	(99)	−1189	(99)	1259	(65)	309	(23)	91	(4.5)	288	(120)
Period 2050–2099																
RCP4.5	79.1	(5.2)	9.66	(1.1)	−1176	(118)	−1087	(119)	1181	(87)	294	(22)	91	(4.6)	297	(149)
i_RCP4.5	81.4	(4.7)	9.66	(1.1)	−1220	(104)	−1129	(104)	1227	(73)	304	(21)	91	(4.6)	311	(129)
RCP8.5	87.6	(6.2)	8.65	(1.2)	−1073	(159)	−977	(159)	1072	(112)	286	(25)	89	(4.6)	292	(197)
i_RCP8.5	90.8	(6.2)	8.65	(1.2)	−1114	(144)	−1015	(144)	1121	(97)	293	(25)	89	(4.6)	311	(175)

predicted a general reduction in the growing cycle length for maize, especially in central Europe. A reduction from 6 to 22 d for maize cultivation in RCP4.5 and up to 8–29 d in RCP8.5 was also forecasted by de Souza et al. (2019) for Brazil conditions using DSSAT-CERES-Maize. Moreover, the consistent reduction in maize production observed with

the climate scenarios in our study is most probably due to the shorter growing period (−8 to −22 d), characteristic of the spring crops. Concerning wheat, the magnitude of reduction in the length of growing cycle is consistent with the findings of Yang et al. (2019) for the Mediterranean area, who fore-

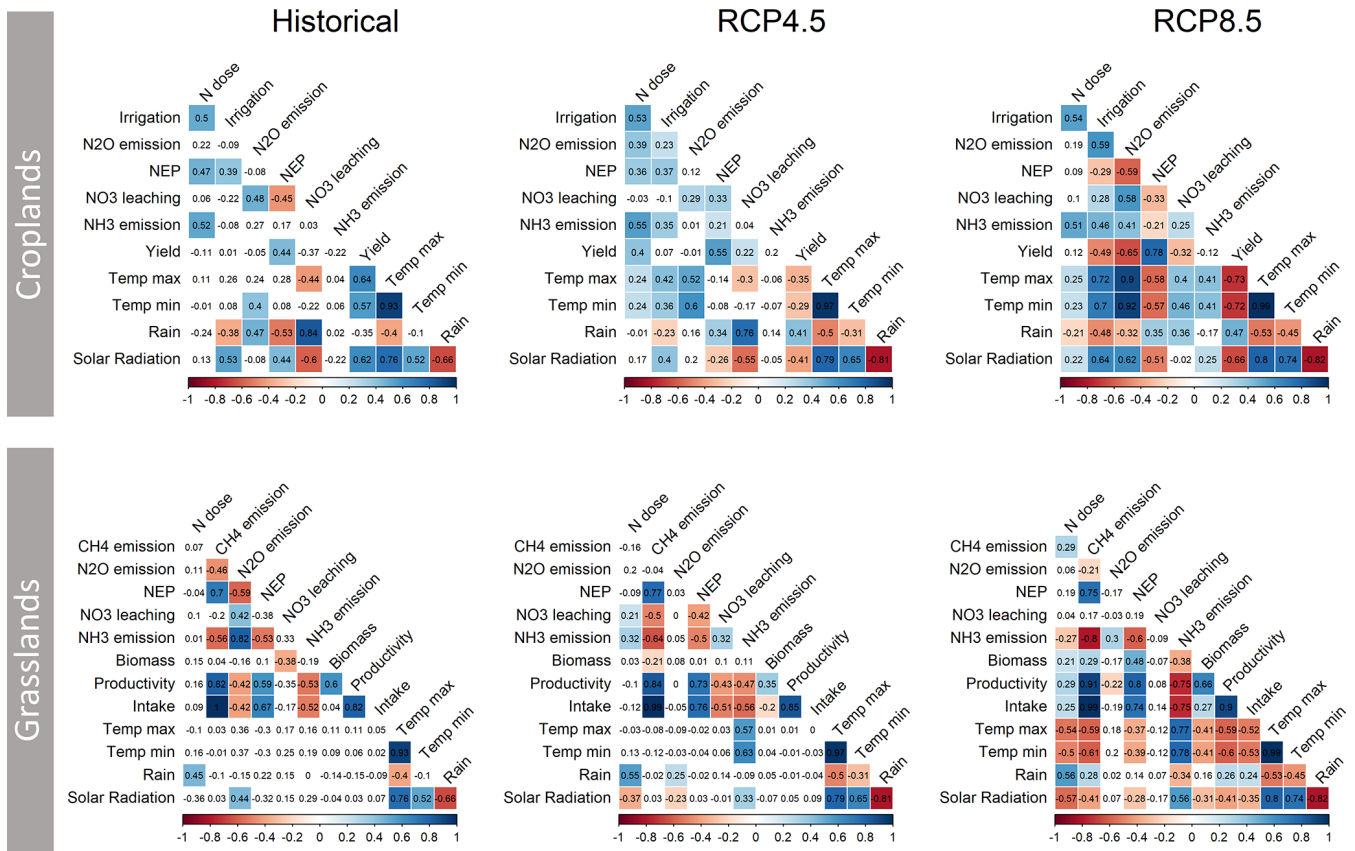


Figure 12. Correlation matrixes for croplands and grasslands considering the most interesting indicators for the objectives of this study. Correlation is presented for the historical period (1978–2004) and for the RCP4.5 and RCP8.5 scenarios. For croplands the irrigable scenario is shown here, while the results for the irrigated scenario are shown in Fig. S8. Coloured squares mean significant results (p value < 0.05).

casted up to -26 d with the STICS model compared to -22 d of our simulations.

Our findings confirmed that climate change will have a regionally distributed impact (Howden et al., 2007; Challinor et al., 2014; Parry et al., 2005; Lobell and Tebaldi, 2014) even in the scenario that includes mitigation measures to offset climate change (RCP4.5), creating the opportunity to the design cropping systems with multiple crops in a year. Multiple cropping can represent a viable alternative in regions with long growing seasons and where water (rain or irrigation) and solar radiation are not limiting factors (Mueller et al., 2015; Waha et al., 2020), as well as where cardinal temperature requirements for crop and varieties are met. Furthermore, our study confirm that a certain number of actual crops and varieties could be cultivated in Europe, even in the worst climate projection. These crops could potentially yield higher production than today, especially at high latitudes, while an overall reduction in crop production is forecasted for low European latitudes.

Finally, the production levels of cropland and grasslands are in line with the available historical data (see Sect. 3.1.1) and the recent – albeit scarce – literature, making this study

coherent and representative. Regarding the climatic projections, yields estimated with the DayCent model (Lugato et al., 2018) for the RCP4.5 scenario in the period 2015–2099 reported an average over Europe of $4.34 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ (ranging from 3.69 to $4.90 \text{ t DM ha}^{-1} \text{ yr}^{-1}$), which is in line with our estimation of $4.49 \text{ t DM ha}^{-1} \text{ yr}^{-1}$ (ranging from 3.55 to $5.49 \text{ t DM ha}^{-1} \text{ yr}^{-1}$) predicted for the same period and climate projection. Assessing the effects of climate change in the European croplands and grasslands, our study can provide support for the identification of climate-smart practices. Among these, the modulation of crop sowing dates and the implementation of irrigation represent possible solutions in the short to medium term to prevent water stress (Lehmann et al., 2013).

Sowing date. Shifting sowing dates represents a promising adaptation to overcome yield drops (Olesen et al., 2012). Accordingly, our results showed that earlier sowing dates are expected for spring-sown crops under future climate scenarios compared to historical dates. Differences between historical and future sowing dates ranged from 0 to -5 d for both RCP4.5 and RCP8.5 scenarios approaching 2050, whereas at the 2100 horizon earlier sowing dates are predicted with

differences of -5 and -7 d for RCP4.5 and RCP8.5, respectively. This evidence shows that climate change allows significantly more advanced sowing in Europe, as confirmed by the review of Tubiello and Rosenzweig (2008). For winter-sown crops, sowing dates are extended in a range from $+5$ to $+9$ d moving towards 2050 and to $+13$ d at the end of the century for RCP4.5. These increases were greater in RCP8.5, ranging from $+7$ to $+13$ d moving towards 2050 and reaching $+19$ d moving towards 2100. The extension of irrigation in all simulated crops in Europe had a negligible influence on the length of the crop cycles, as discussed by Minoli et al. (2019), despite an increasing demand of water over the course of the century.

Irrigation. Water demand has been shown to increase by $+6\%$ during the first half of the century, to slightly decrease in the second half for RCP4.5 (-2%) and to increase again for RCP8.5 ($+23\%$). These variations are in line with the results of the multi-model approach used by Wada et al. (2013) analysing the uncertainty in the response of different hydrological models over Europe. These authors showed a decrease in water demand for irrigation moving towards 2100 in Europe of $<5\%$ for RCP4.5 and a rise of $>20\%$ for RCP8.5. Furthermore, from our study we observed that water demand assumes a strong regional variation in Europe, with low latitudes needing 227 mm yr^{-1} on average over the historical period (mean 1985–2004), which is an order of magnitude higher than mid-latitudes (29 mm yr^{-1}) and high latitudes (9 mm yr^{-1}). These proportions between the latitudes remained unvaried over the course of the century, whereas middle and high latitudes displayed a $+20\%$ increase in the evapotranspiration deficit approaching 2050 (mean 2030–2049) compared to the historical period, in both climate scenarios. This phenomenon observed for low latitudes is strictly related to climate perturbation (i.e. a strong increase in air temperature and reduction in rainfall), which increased crop water demand (Olesen et al., 2011). Furthermore, the increase in water demand even in middle and high latitudes confirms that irrigation needs to be supplied even for the crops that are now commonly rainfed (e.g. spring and winter soft wheat, spring barley, sunflowers, rapeseed). By 2100, the volumes of water needed for European croplands were largely reduced to below the quantities observed during the historical period, especially for low latitudes. These findings underline that even with high availability of irrigation water, the reduction in the crop growing cycle for the actual crop varieties – which sharpens towards the end of the century – is a more decisive factor to determine drops in crop yields. This is more evident for grain maize, the most water-demanding crop (Fig. 3), which needs an additional $+35\text{ mm yr}^{-1}$ (average over Europe) to support production by 2050 compared to the historical period. Approaching 2100 water demand for grain maize remains identical to the historical period for RCP4.5, while it is increased ($+25\text{ mm yr}^{-1}$) for RCP8.5. Conversely, water demand for winter soft wheat remained constant throughout the century for both RCP4.5 and RCP8.5

scenarios, whereas *i*_RCP4.5 and *i*_RCP8.5 scenarios confirmed an increasing water demand of about 50 mm (average over Europe; Fig. 3), as also confirmed by Yang et al. (2019) for the Mediterranean regions.

4.2 Effect of climate on N_2O and CH_4 emissions

N_2O . The estimation and the projection of N_2O emissions in the historical and the climate change scenarios improved upon previous studies over Europe. Lugato et al. (2017) estimated averaged emissions ranging from 1.18 to 2.63 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ in the period 2010–2014 for both cropland and grassland production systems with the DayCent model. In comparison with Lugato et al. (2017), we found similar results for the Mediterranean latitudes (about 1 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$), while we predicted significantly lower emissions for central Europe (1.1 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$, this study), as well as at higher latitudes (0.96 kg N $\text{ha}^{-1}\text{ yr}^{-1}$, this study), compared to the 3 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ forecasted by Lugato et al. (2017). Indeed, lower emissions at high latitudes were also observed by other studies (e.g. World Bank, 2021; Eurostat, 2017; Stehfest and Bouwman, 2006; Wells et al., 2018). Other research studies in the field were also within the range of our results; e.g. Reinds et al. (2012) estimated emissions ranging from 1.1 to 2.4 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ for arable lands for the year 2000, and de Vries et al. (2011) estimated 0.27 and 0.38 Mt N- $\text{N}_2\text{O yr}^{-1}$ for fertilisers and manure and from grazing, respectively. Recently estimation by Eurostat (2017) reported values of 0.39 Mt N- $\text{N}_2\text{O yr}^{-1}$ (184.8 Tg $\text{CO}_2\text{ eq.}$) for the year 2015 based on a lower-tier methodology, while our study reports a lower value equal to 0.17 Mt N- $\text{N}_2\text{O yr}^{-1}$ (80 Tg $\text{CO}_2\text{ eq.}$) for the same year. Based on global inventories, Tian et al. (2020) reported emissions from European agriculture on the order of 0.51 Mt N- $\text{N}_2\text{O yr}^{-1}$ for the decade 2007–2016, which are significantly higher than those found in this present study (0.17 Mt N- $\text{N}_2\text{O yr}^{-1}$) for the same period. In addition, the estimation by Tian et al. (2020) also included manure management and aquaculture and suffers from high uncertainties given by the quality of the data and statistics used as input and, foremost, by the use of default emission factors. Regarding climate projection studies, Lugato et al. (2018) quantified N_2O emissions for croplands in the RCP4.5 scenario, reporting losses of 1.81 and 1.77 kg N- $\text{N}_2\text{O ha}^{-1}\text{ yr}^{-1}$ for the first and the second part of the century, respectively. These estimations were comparable to, although slightly higher than, the emissions for croplands issued from our study, both for the first part ($1.53 \pm 0.23\text{ kg N ha}^{-1}\text{ yr}^{-1}$) and for the second part ($1.66 \pm 0.28\text{ kg N ha}^{-1}\text{ yr}^{-1}$) of the century.

Our study highlighted that crop type is a significant determinant of the EFs of fertilisers, with most of the cereals having a low EF (barley, fodder maize, soft spring wheat and rapeseed; mean of 1.1 %) and pulses, soybean and potato a high one (mean EF of 3.1 %) during the 1985–2004 integration period. The highest EF for leguminous crops in-

dicates that the management of fertilisation for these crops or for the rotation itself can be improved. Finally, information about crop-specific EFs turns out to be useful to design improved crop successions and to compile emission inventories (Myrriotis et al., 2019). However, our results were higher than the 1 % default value defined by the IPCC guidelines for the N applied to agricultural soils, mainly because we considered only the N applied as fertiliser. Anyway, this default factor shows large uncertainties at local to regional scales due to the scarcely captured dependence on spatial diversity of the management, pedoclimatic, and soil physical and biochemical conditions (Leip et al., 2011; Reay et al., 2012; Shcherbak et al., 2014; Cayuela et al., 2017), which, however, are considered in our study. We observed that N₂O emitted from croplands had a significant ($p < 0.05$) and positive correlation with rainfall ($r = 0.47$), as well as minimum and maximum air temperatures during the historical period (Fig. 12). The correlation with the minimum and maximum air temperatures increased significantly depending on the climatic scenarios ($r > 0.5$ for RCP4.5, and $r > 0.9$ for RCP8.5; Fig. 12), while the relation to rain became negative for RCP8.5 ($r = -0.32$). This trend inversion is probably connected to the strict dependency of N₂O emissions on the length of the crop growing period rather than the yearly cumulated rainfall, which can occur outside of the cultivation period, as also stated by Shcherbak et al. (2014). Accordingly, the correlation from N₂O and the irrigation amount, which occurs during the cultivation period, rose in the climate scenarios ($r = 0.23$ and $r = 0.59$ for RCP4.5 and RCP8.5, respectively). The rise in the projected temperature in the climate scenarios displays a latitudinal impact with N₂O emissions, which is directly correlated at middle and high latitudes for croplands ($r > 0.5$ for RCP4.5, and $r > 0.9$ for RCP8.5) and at low latitudes for grasslands ($r > 0.45$ for RCP8.5 and $r > 0.75$ for RCP4.5). Precipitation in the mild climate has a direct influence on N₂O emissions ($r = 0.25$) at mid-latitudes for both production systems and also at high latitudes for croplands. Precipitation is anticorrelated with the N₂O emissions in the RCP8.5 scenario at middle and high latitudes for croplands and at low latitudes for grasslands. Moreover, N₂O emissions from cropland and grasslands were both positively correlated with soil clay content ($r > 0.5$, $p < 0.01$; data not reported) for values lower than 32 %, as higher clay content can promote complete denitrification (Weitz et al., 2001).

CH₄. Methane emissions were mainly concentrated in the European regions with the highest density of grazing animals, as also observed by Vuichard et al. (2007). The values of the emissions simulated for the historical period ($6.71 \pm 0.4 \text{ kg C-CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$) were in the range of the experimental trials from central European grasslands (-2 to $108 \text{ kg C-CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$) discussed by Hörtnagl et al. (2018) and lower than the findings of Soussana et al. (2007), who reported typical emissions of $41 \text{ kg C-CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ with animal densities comparable to our

study. Our simulations were slightly lower than the simulations of Chang et al. (2015), which found emissions in a range of $18.7 \pm 7.9 \text{ kg C-CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ (period 1961–2010) over Europe with the ORCHIDEE-GM model, and lower than Vuichard et al. (2007) with an average of $108 \text{ kg C-CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ (period 1994–2003) using the PaSim model but with a higher stocking rate. CH₄ emissions decreased towards the end of the century, especially in the scenario RCP8.5 (-9% compared to the historical period), due to reduced biomass productivity of grasslands that lessened the intake of animals (Fig. 2) and the stocking density, which declined to -8% compared to RCP4.5 in the last decade of the century. Reduction in the stocking density was also foreseen by Chang et al. (2015). With regard to climatic changes, the rise in temperatures and the reduction in rainfall could directly act on reducing protein content and forage digestibility (process not simulated at the moment), possibly leading to reduced N₂O losses from manure and urine in pastures. However, this mechanism could be offset by an increase in CH₄ losses (Wilkinson and Lee, 2017).

Nitrogen use efficiency (NUE). We observed an increase in the NUE for the European croplands, especially for the mild climate change projection. In fact, compared to the historical period, in the RCP4.5 scenario there is a reduction in the correlation between N₂O and the other N losses (NO₃ and NH₃) and crop yield (Fig. 12). At the same time, there is an intensification of dependence on the N dose. Indeed, with a constant amount of N applied in the rotations over the simulated years, both NO₃⁻ and NH₃ losses were reduced over the century (data not reported) and crop yields increased until – at least – 2050. This indicates a potential increase in the NUE. Our findings were supported by the study of Kanter et al. (2016), who observed an increase in the NUE by 2050 related to the forecasted increasing yields. The improvement in NUE indicates a key factor to reduce negative environmental effects and mitigate GHG emissions (Maaz et al., 2021). UNEP (2013) indicated that NUE improvement could reduce N₂O emissions by more than 30 % by 2050 in the RCP8.5 scenario. On the other hand, our results indicate that in the RCP8.5 scenario the correlation between N₂O emissions and the N dose is lost, and a significant negative correlation ($p < 0.05$) between yield and other nitrogen losses took place, indicating a reduction in NUE. This lack of a relationship is most probably connected to the interannual variability in N₂O emissions in the strongest climate scenario and in the second part of the century. Higher NUE is typical of low latitudes in Europe, which benefit from generally higher yield and lower N losses compared to the middle and high latitudes (Sutton et al., 2011). Improving actual agronomic practices to increase crop yield or reduce reactive N losses has a direct and positive impact on the NUE (Lassaletta et al., 2014; Myrriotis et al., 2019). In this context, irrigation represents a fundamental intensification practice to counteract the effects of climate change on crop production. In our case, the extension of the irrigation to all cropping

systems in Europe significantly decreased N losses (-5% for NO_3 leaching and -4% for NH_3 emissions, on average, for both *i_RCP4.5* and *i_RCP8.5* scenarios) and contributed to increasing crop yields (Fig. 2), leading to a potential increase in NUE.

Regarding grasslands, we observed a weak relationship between N_2O emissions and applied doses of N as fertiliser. This is mainly due to the calculation of the doses of N, which is a function of the specific animal load, the legume fraction, mowing events, and the available quantity of mineral and/or organics fertilisers for each simulation unit. During the historical period, N_2O emissions were positively correlated with NO_3 and NH_3 losses and negatively correlated with production, representing a potentially low NUE. Moreover, N_2O emissions in grassland are anticorrelated with CH_4 emissions. CH_4 emissions are rather positively related to biomass production and livestock intake. Therefore, poor biomass production could potentially lead to increased N_2O emissions, due to low NUE, and thus decreased CH_4 losses, due to low livestock intake. Surprisingly, N_2O emissions in grasslands were weakly correlated with meteorological variables, especially minimum and maximum air temperatures, whereas a relation to rain and solar radiation is noticeable for RCP4.5 and is not evident for RCP8.5. As observed for croplands, the relation between N_2O and NH_3 emissions is positive, especially for the RCP8.5 scenario, indicating a potential reduction in the NUE.

4.3 Potential carbon stock

NEP. The NEP represents a simple indicator of carbon storage potential since it does not account for C removal in terms of yield, animal intake or crop residues. Our results concerning croplands confirmed a net potential storage of C during the historical period ($-3403 \pm 214 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$) and are directly comparable with those of Kutsch et al. (2010), who observed fluxes of $-2400 \pm 1130 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ based on field measurements in multiple sites in Europe. During climate scenarios, a significant decline in C uptake was predicted for the northern cropping systems (British Isles, Scandinavian Peninsula) and the Mediterranean area. This is most probably due to the increase in soil heterotrophic respiration caused by climatic factors and to a potential reduction in NEP (Fig. S9), respectively, as also reported by Kirschbaum (1995). Further decreasing values of NEP (towards a carbon stock) are evident in central and north-eastern Europe, especially in the first part of the century. A substantial increase in NEP in croplands was predicted towards the end of the century for the RCP8.5 scenario. This increase is most probably related to low levels of heterotrophic respiration (i.e. microbial respiration due to decomposition processes of soil organic matter) associated with partial soil coverage (e.g. no cover crops) of the simulated crop successions, as reported by Emmel et al. (2018).

Lower average NEP values were observed in grassland systems compared to croplands. This is related to the continuous removal of biomass by grazers; the generally higher SOC content in the topsoil; long-term land use (Morais et al., 2019); and the higher heterotrophic respiration that characterises these soils, especially when extensively managed (Bahn et al., 2008). This evidence has also been described by Chang et al. (2015), who simulated an average of $-570 \pm 210 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ between 1961 and 2010 for Europe, slightly lower in absolute value than the mean value simulated by our study of $-622 \pm 62 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ in the historical period (Table 1).

In general, areas where the heterotrophic respiration is enhanced by climatic drivers or by a high amount of SOC would lead to lower NEP values (Chang et al., 2017). This is the case for the north-east of France and the British Isles, while for the Scandinavian Peninsula and north-east Europe, which are characterised by low C and low heterotrophic respiration, NEP reached higher values. These results underline that in view of expected increasing productivity by 2050, storing additional (new) carbon will be more challenging in areas with high SOC levels (Hassink and Whitmore, 1997), mainly due to high levels of heterotrophic respiration. Finally, grasslands remained a potential sink for C during the historical period, which is in line with experimental measurements performed in the last 2 decades, e.g. $-2470 \pm 670 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ reported by Soussana et al. (2007) and from -910 to $-17\,830 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ reported by Hörtnagl et al. (2018).

N_2O emissions were able to offset (reduce) the C sequestration potential of croplands. Offsets were on the order of 5.4% ($184 \text{ kg C-CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$) for the historical period and the first part of the century and rose up to 6.1% and 7.5% in the second part of the century for RCP4.5 and RCP8.5, respectively. The extension of irrigation to all European arable lands reduced these gaps thanks to the increased values of NEP (offsets of 5.4% and 7.1% for *i_RCP4.5* and *i_RCP8.5*). Even though few data are available in the literature regarding the CO_2 storage potential for croplands (Emmel et al., 2018), our results confirmed that croplands may act as a potential sink of C when C exports by harvest are neglected (Buysse et al., 2017; Ceschia et al., 2010). N_2O and CH_4 emissions in grassland systems were able to offset NEP during the historical period by 17% and 1% , respectively. These results are partially compatible with the studies reported by Soussana et al. (2010), who displayed offsets over Europe of 34% and 10% for N_2O and CH_4 , respectively. During climate projections, offsets rise to 22% for N_2O and 1.2% for CH_4 moving towards 2050 for both RCP4.5 and RCP8.5. In the second part of the century N_2O emissions offset the potential carbon sequestration by 26% and 52% for RCP4.5 and RCP8.5, respectively, while the offset potential of CH_4 ranged between 1.2% and 1.9% for RCP4.5 and RCP8.5, respectively.

4.4 GHG emission budget

The NGB, calculated by subtracting the other non-gaseous C fluxes (i.e. exports by harvest and crop residues, imports by manure) from NGHGE, indicated that European agricultural surfaces are a net C source. The most important components that determined these losses were the C exports – yield ($F_{C\text{-harvest}}$) and crop residues ($F_{C\text{-residues}}$) – which varied proportionally to the NEP in the various climatic projections; i.e. the lower the NEP, the lower the yields. For both cropland and grasslands, CO₂ storage potential (estimated from NEP) provided the largest term in the net greenhouse gas exchange (NGHGE), as also confirmed by Jones et al. (2016). Non-CO₂ GHGs, despite being high especially in the RCP8.5 scenario towards the end of the century, have a minor impact on differentiating the two climatic scenarios, although they represent an important component in the overall carbon balance at the European scale (see Table 2). The values of NGB highlight that inputs of C into the system, such as organic fertilisers (two-thirds of the component $F_{C\text{-manure}}$), or actions aimed to recycle a portion of biomass in the field, such as crop residue management, are essential to improve the overall C budget to move towards net storage, as also reported by Ceschia et al. (2010) and Buysse et al. (2017). Moreover, our findings show that the contribution of the exported crop residues corresponded roughly to the whole carbon deficit in Europe. Therefore, crop residue could play a key role in land-based mitigation of anthropogenic emissions, as also reported by Stella et al. (2019) and Haas et al. (2022). This is in line with the “4 per 1000” initiative (Rumpel et al., 2019) promoting the maintenance of soil fertility as a key to achieve GHG mitigation strategies. In addition to the spatial diversity observed in the European agricultural area, the achievement of this goal depends on the complexity of the rural, economic and political structure of the territories (Amundson and Biardeau, 2018). Local policies can be supported by simulation tools such as those used in this study, bearing in mind that their effectiveness can be affected by the omission of large variances given by varied characteristics of small extents (see Sect. 4.5). Finally, irrigation management extended to all European cropping land led to slightly higher C deficits because it is able to increase the stored C (NEP = +3 %), but it also increases the removal of crop residues ($F_{C\text{-residues}}$) and the emission of non-CO₂ GHGs (up to +4 %).

4.5 Uncertainty, limitations and novelty

The extension of field-scale models to regional scales faces several challenges associated with the representation of the systems under study, which can affect the confidence of the model outputs (Challinor et al., 2014; Folberth et al., 2019).

Input data. The input requirement for dynamic crop and grassland models for large and heterogeneous areas is difficult to fulfil (Therond et al., 2011). While soil and climate inputs are directly available from European databases

at different spatial resolutions, details on crop and grassland management (e.g. type and number of inputs, timing of operation, tillage system, crop varieties) are less readily available and represent an important source of uncertainty (Molina-Herrera et al., 2016). In our assessment we used a dataset for cropland constituted by statistical data of crop rotations resulting from a spatial distribution of crops at the NUTS2 scale and by crop succession likelihoods, on a high-resolution scale (1 km × 1 km). This dataset does not include details about intercropping, cover crops, management or crop growth parameters. The absence of plant phenological development data, for instance, is a relevant source of uncertainty in regional assessments (Minoli et al., 2019). This information defines crop growth and the length of the growing season, influencing biogeochemical cycles at different scales and becoming key for future projections. To deal with this lack of information, we calculated crop-specific sowing and fertilisation dates as a function of climate (Ramirez-Villegas et al., 2015), together with the uses of different crop varieties following a latitudinal gradient to fulfil the thermal unit need, N doses and the crop-specific residue management, aiming to reduce the uncertainty in input data (Hansen and Jones, 2000). Furthermore, the use of two different crop rotations per simulation unit attempted to cover a range of uncertainties existing below the spatial resolution of 0.25°, which, however, cannot be assumed to be fully covered by the range of setups presented here. Another limitation of this and other regionalised studies is the deviation in the representation of the quantities within the administrative units, which is related to the scarcity of management data with a fine spatial resolution. For example, the amounts of fertiliser to be distributed in cropping systems which are provided at a regional level show little heterogeneity within the boundaries of the region itself and can mark a sharp transition between adjacent regions. Regarding model parameterisation, in the present work the CERES-EGC model used fixed parameters issued from a calibration over different sites in Europe (Lehuger et al., 2010, 2011; goodness of fit, R^2 is 0.59 to 0.76 for NEP; error of prediction reduced by 6 %–40 % for N₂O compared with the model’s standard parameters). Grasslands, as previously reported, were simulated with a parameter set resulting from a multi-site calibration for a network of European grasslands (i.e. flux tower network; see Ma et al., 2015; goodness of fit, R^2 is 0.4 to 0.9). Likewise, PaSim follows adaptive management based on climate. Since the information concerning the input data is already the result of a scaling process, an uncertainty analysis concerning the input data is not suitable here (Hansen and Jones, 2000).

Calibration of models. To fulfil the task of calibration over large areas, data representing the spatial and temporal variation in models’ parameters are required. Although both models have been calibrated and verified with direct observations under various pedoclimatic and management conditions at the field scale, comprehensive studies aimed at calibrating these and other models with spatially extensive time series

are still scarce (Balkovič et al., 2013; Lehuger et al., 2010; Lugato et al., 2010; Vuichard et al., 2007). Data aggregation over the same extent can be used to assess model representations, even if they do not represent the field-scale conditions for which the models have been originally calibrated (Lugato et al., 2017; Therond et al., 2011; van der Velde et al., 2009), exposing models to a broader range of conditions (e.g. weather and soil characteristics). Indeed, dealing with lacking and heterogeneous input data requires different procedures of downscaling and upscaling for the different data types, which potentially contribute to feeding the uncertainty in the representation. Consequently, projecting responses of regional models under future climate scenarios requires careful understanding of input and model uncertainty (Asseng et al., 2013; Challinor et al., 2009). This is the reason why the two periods of temporal aggregation considered in the present study, historical and climate scenarios, provide outcomes with different levels of confidence. In the historical period, results are obtained based on the spatial aggregation of real (statistical) data by means of models parameterised with current soil, climate and management conditions. The outcomes of the climate scenarios deal with the uncertainty related to the sensitivity of the model parameters and their algorithms to climate variables, which is expected to be different due to the diverging intensities of the two climate projections and the different conditions in the near and the long term (2100). For this reason, direct comparisons between the two aggregation periods should be made but with caution.

Model validation. Data quality and availability also prevent the validation of regional-scale models, even if the literature reports some effort (Challinor et al., 2009; Faivre et al., 2004; Niu et al., 2009). Comparing the model outputs with statistical data aggregated at the regional scale (production) allowed us to obtain indications about the magnitude of simulated variables at the same spatial extent. Furthermore, assessing the ranges of the model outputs, e.g. yield, with measured data and over Europe ($R^2 = 0.92$, $p < 0.01$, for croplands, Fig. S1; $R^2 = 0.68$, $p < 0.05$, for grasslands, Fig. 1), as well as other modelling interpretations (even if grounded on different approaches), contributed decidedly to increasing the reliability of our estimations.

The literature includes similar studies aiming to estimate crop and/or grassland production, GHG emissions, and carbon storage at the European scale. Lugato et al. (2014) created a database, based on EU statistics, of soil, climate and land use for grassland and cropland to simulate SOC with the CENTURY model, which worked at a monthly time step. This dataset was subsequently enhanced with the direct soil observation network over Europe (LUCAS – Land Use and Cover Area frame Survey) to estimate N_2O emissions from cropland with the DayCent model, at a daily and long-term resolution (Lugato et al., 2017). Finally, these authors used an effective method of filling and scaling the simulated results by means of a meta-model, although adding a potential additional source of uncertainty. Regarding grasslands,

Chang et al. (2015) used the ORCHIDEE-GM model (which contains the management equations derived from PaSim) to simulate the greenhouse gas balance in Europe, later extending their analysis with climate change scenarios (Chang et al., 2017). Blanke et al. (2018) improved the LPJ-GUESS global model to be applied to grasslands and to estimate the carbon and nitrogen balance with future climate scenarios. Compared to the studies mentioned above, our work combined two state-of-the-art models specific to the systems under study, producing both separate and joint results on croplands and grasslands. The novelty of this work is also based on the use of dynamic management with specific crop rotations, instead of exploring one crop or a few crops (e.g. Sansoulet et al., 2014; Yang et al., 2019), and the work was conducted at a finer spatial resolution than, for example, that of Vuichard et al. (2007) with the PaSim model or Leip et al. (2008) with DNDC and agrees with the resolution used by Chang et al. (2015) for grassland. Recent studies at an ever finer spatial scale have been proposed over France with the STICS model (Launay et al., 2021). Albeit aggregated in gridded simulation units, our work considered a variety of pedoclimatic conditions over Europe and is not based on an extrapolation of a few points or on a single European area (Ceschia et al., 2010; Kutsch et al., 2010; Myrriotis et al., 2019; Soussana et al., 2010).

Finally, knowing and controlling the sources of uncertainty from regional applications could be a key to improving decision support tools for the design of policies. In this context, providing a range of possible outcomes, the application of multi-model ensemble (Ehrhardt et al., 2018; Martre et al., 2015; Sándor et al., 2018; Rosenzweig et al., 2013) at a regional scale could represent a valuable tool to tackle this source of uncertainty. Increasing the spatial resolution of the input dataset we used (e.g. weather and management data) could also represent a key to further reduce uncertainties from input data in future large-scale applications (Folberth et al., 2019; Hoffmann et al., 2016; Stella et al., 2019).

5 Conclusions and perspectives

In this study we presented the combined spatial analysis of two specific models for crops and grassland to quantify the effects of climate change on European agricultural systems. Results clearly showed that production will be stable in the first half of the century, while a strong reduction will occur during the second half of the century, especially at low latitudes and mainly due to a reduction in the length of the growing cycle. Non- CO_2 greenhouse gas emissions were triggered by rising temperatures, increasing significantly in the second part of the century. At the European scale, both grasslands and croplands are potential carbon sinks, although this potential is reduced by the negative effects of climate change on productivity. Biomass removal from the agricultural surfaces (yield, hay and animal intake), combined with the re-

removal of crop residues, shifts the balance towards a net loss. In this framework, the introduction of carbon with fertilisers and dung was not able to counterbalance this removal of C, while the positive effect on the carbon stock offered by the return of crop residues needs to be further investigated, together with the potential shift in the net greenhouse gas balance. Our study highlighted that further carbon storage in areas already characterised by high SOC levels will be more challenging in the future. The extension of irrigation to all European croplands indicated a significant increase in water demand over the next few decades for most of the European croplands, whereas the benefit in terms of crop yield will not contribute substantially to filling the gap of carbon losses. Our findings show that productivity, GHG emissions and changes in the soil C stock have a heterogeneous spatial distribution over Europe. This underlines the need for targeted agricultural policies at the territorial scale aimed at avoiding the risk of significant reductions in productivity and mitigating the negative effects of climate change, foremost expected in the second half of the century. Accordingly, this transformational adaptation has to deal with socio-economic and political dynamics, as well as land suitability (Fischer et al., 2005; Chaudhary et al., 2018; Martin-Lopez et al., 2019). This work provides a database on cultivation and management of cropland and grassland at a detailed spatial level. Data can be improved to reduce uncertainty and increase the resolution and further exploited to test different management options, new or new combinations of agro-ecosystem models, climate projections, crop varieties, or floristic compositions to support future action to maintain or enhance agricultural sustainability.

Data availability. The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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