Ref.: Ms. bg-2021-241 Biogeosciences

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

Reviewer#1

General consideration:

This manuscript shows the impacts of climate change in the European cropland and grassland production systems towards year 2100. Specifically, by using two biogeochemical models, the work focuses at assessing changes in plant productivity and biogenic GHG (N2O, CH4, CO2) balance. The paper is well detailed and structured, the language is appropriate and is fluently flows. However, to my opinion, some very important weaknesses are presents:

We thank the Reviewer#1 for the in-depth analysis of our work and the detailed comments which allow us to amend and improve the manuscript. All the critical points raised have been taken into consideration and addressed/discussed, as detailed in this document (in blue).

1. The novelty of the paper is quite low. Further modelling studies have been carried out at larger scale to assess changes in productivity and GHG emissions. The 2100 threshold is quite far and, even in the view of the EU policies mostly focused at nearest GHGs thresholds, the provided results risk to be very speculative and not very close-to-reality to provide suitable information for policymakers as suggested in line 74-75.

First part of the remark, novelty of the work. Literature reports similar European-scale studies that aim to estimate crop and grasslands production, GHG emissions and carbon storage at regional scale (e.g. Lugato et al., 2017; Lugato et al., 2018; Leip et al., 2008; Chang et al., 2017; Blanke et al., 2018). Unlike these studies, our study is based on two state-of-the-art specific models for the two systems under study, with detailed management options and producing both separated and joint results on croplands and grasslands. Moreover, unlike the mentioned studies, our work has a finer spatial resolution (see Vuichard et al., 2007, Leip et al., 2008; Ciais et al., 2010; Lugato et al., 2014; Iglesias et al., 2012) agreeing with the study presented by Chang et al. (2015 and 2017) which, however, deals only with grasslands. Furthermore, our work considers a variety of pedoclimates, albeit aggregated in simulation units, and is not only based on an extrapolation of a few points or on a single European area (Myrgiotis et al., 2019; Kutsch et al., 2010; Ceshia et al., 2010, Soussanna et al., 2010; Lugato et al., 2017; Lugato et al., 2018). Our work considers dynamic management by crop type or grasslands in comparison to e.g. Lugato et al. (2017), Ciais et al. (2010) and Leip et al. (2008). Finally, regarding novelty, we use specific crop rotations which are essential for understanding the dynamics of C storage and N_2O emissions in soils (13 crops in specific succession for each simulation unit) and not based on one or a few specific crops, as reported by other Authors (e.g. Sansoulet et al., 2014, Yan et al., 2019).

Second part of the comment, 2100 threshold. The use of quantification methods based on process-based biogeochemical models, as we used here, represent a suitable tool to estimate the long-term effects of management options or climate perturbation on productivity, GHG emissions and carbon dynamics in the long period (e.g. Farina et al., 2020). In fact, the quantification of SOC dynamics from agricultural surfaces over space and time is challenging as the effect of management practices may take years to occur and experimentation became difficult for testing multiple agricultural practices over large areas (Heiskanen et al., 2012). Similarly, GHG emissions, although more realistic in the near future, are still related to long-term dynamics (Guenet et al., 2021), justifying their representation over long-term.

As remarked by Reviewer#1, the horizon of 2100 is far to guide European policies and the quoted sentence "*This study represents the baseline to support and identify future actions targeted to maintain productivity and reduce environmental impacts*" does not reflect the main aim of this work. Our intention is to provide technical (databases and models) and scientific (outcomes) support for policies. With this work, we are able to provide, with an acceptable degree of uncertainty, the evolution of the agro-ecosystems in the near future (e.g. until 2030) to observe changes in biogeochemical cycles (i.e. GHG emissions or SOC changes). Projection at the horizon 2100 provides, with another degree of uncertainty, the impacts of future climate and business-as-usual management on the same variables. To reflect that, the sentence will be amended as *"This study provides near and long-term projections on main agro-ecosystems variables to support and help to identify possible actions targeted to maintain productivity and reduce environmental impacts*".

This represent a sound remark and we're intended to point out the relevance and the differences between the near and long-term estimations at the beginning of the discussion section (§4) to better guide the interpretation of the results.

2. Modelling works do need appropriate model parametrization such as climate variables, soil properties, vegetation parameters and management. Whereas climate and soil properties are clearly reported, several information in the other components are missing or shows very low confidence. For instance, for the management characteristics, I appreciate the effort of the authors to obtain all these information. However, some parameters need to be better explained and discussed. For instance, sowing dates and fertilization were imposed but, for sure, these cannot reflect all the possible variability observed in the whole EU. I understand the need to impose fixed parameters for running the model, however it is also necessary to indicate the results can be affected by uncertainties due to the application of these fixed parameters. My main concern is about crop parametrization. In line 175-176 authors indicate a crops parametrization based on those applied in previous/other works. However, no reference has been reported. Also, I was wondering how authors were able to retrieve and summarize all these crop/grassland information since modelling study are often carried out at single point/area, with different parametrization for the same crop over different areas, and do not report these data. This is also true especially for grasslands where, as the same authors says, very low information are presents. There is no explanation about these parametrization (i.e. water efficiency, radiation use efficiency, maximum and minimum productivity, etc.) were found, from which studies, and how

these parameters were summarized to find the most representative/suitable for each of the applied crops.

First part of the comment, model parameterisation. Although both models (CERES-EGC and PaSim) have been calibrated and verified with direct observations under various pedoclimatic and management conditions at the field-scale (see all the references below, and the review of Brilli et al., 2017), comprehensive studies aimed to calibrate model performances with spatially extensive time series and variables, as well as model sensitivities with climate perturbation, are scarce (Lehuger et al., 2010, Vuichard et al., 2007). This is valid for the model we used here and other biogeochemical models (e.g. Balkovic et al., 2013, Lugato et al., 2010). Calibrating biogeochemical models over large regions is challenging. Wide-ranging experimental dataset that allow testing the interactions of multiple variables (GHG, soil, water, ..) are scarce and fragmented. Aggregated data from regional statistics (Eurostat, FAOSTAT, ...) are insufficient to parameterise the models, as they do not represent the field-scale conditions for which the models were originally developed (Therond et al., 2011). Furthermore, as Reviewer#1 specified, soil and daily climate input data are often available from existing databases at different spatial resolution. On the other hands, spatially and temporally information on crop type, parameters and management are less readily available (e.g. Leenhardt et al., 2010). Dealing with scarce input data and spatialised measurement requires different procedure of downscaling and upscaling for the different data types. This will feed the uncertainty of the outcomes. These aspects will be presented and discussed in a specific chapter (§4.5 "Uncertainty and limitations of this study") since, with regards to model parameters, knowing the source of uncertainty is the key to understand and exploit our outcomes.

Second part of the comment, input data. Regarding crop and grassland input management in our simulations, certain parameters such as sowing dates, fertilisation schedule as well as cutting dates were not prescribed. They were dynamically calculated per year and for each simulation unit as a function of the specific climatic conditions. To avoid e.g. issues related to shorter crop cycles due to early sowing dates in warmer climates we opted for different crop varieties following a latitudinal gradient to fulfil the thermal units needed. The selection of varieties has been done following the published studies for winter soft wheat, pulses, maize, barley, rapeseed (see references on the following paragraph) and, for the other crops, based on the modellers' experience by using the CERES-EGC varieties database. Moreover, as described also by Minoli et al. (2019) crop phenological development constitutes a relevant source of model uncertainties in regional assessment, which will be cleared and discussed as well in the above-mentioned chapter regarding uncertainty (§4.5). PaSim model did not use a specific calibration of grasslands over Europe, but was run with a parameter set resulting from a mullti-site calibration for a network of EU grasslands (i.e. flux tower network, see Ma et al. 2015). Likewise, PaSim follows an adaptive management based on climate.

In relation to previous work used for crop parameterisation in Europe - and more specifically in France, Germany, Italy, Sweden, Denmark, UK - we can mention Drouet et al. (2011), Ferrara et al. (2021), Goglio et al. (2013), Lehuger et al. (2009), Lehuger et al. (2011), Rolland et al. (2008), Wattenbach et al. (2010), Haas et al. (2021) that all used, parameterised and tested the CERES-EGC model. Concerning grassland, PaSim has been calibrated in UK, Ireland, Hungary, France, Germany, Italy, Portugal, Spain, The Netherlands by different studies, e.g. Lawton et al. (2006), Calanca et al. (2007), Gottschalk et al. (2007), Vuichard et al. (2007), Ma et al. (2015), Sandor et al. (2016). These references will be reported in the text of the manuscript as suggested by the Reviewer#1.

3. My main concern is the point 3.1.1., model validation. Model validation should provide a confirmation about the model capability to represent the crop growth, development, and production in different environment. However, looking at picture 1a, does not seem that models are able to reproduce the correct behavior of each single crop. Putting all crops together may create an inthrinsic error and does not indicate if each single crop is well reproduced. For instance, looking at sugar beet or potato, I'm not able to see a proper correlation between modelled and observed crops. In order to provide a robust validation, each crop should be singularly validated and then reported, so as readers are able to see the model confidence and robustness at reproducing the crops. This is needed also to provide robust information about the expected changes due to climate change. Therefore, I suggest authors to provide single validation for each crop and then summarize them in scatterplot or table with the relative statistics. Concerning grasslands, results are very poor for all areas. For instance, for the sole Mediterranean data (L272) the overestimation of 55% do not allow to indicate these data as robust enough to be accepted. This overestimation led to unplausible results under future conditions, resulting not useful and misunderstandable for readers and policymakers. I understand the lack of data, however more recent and affordable information on productivity could be taken by remote sensing and new analysis may be done to provide more robust results. I understand the effort of the authors, but grasslands systems are very complex and sensitive to climate change, especially considering the dynamics involving water reduction and species changes. These results do not take in account changes in composition that, in turn, also affect productivity, neither provide robust statistics. Finally, as indicated for crops, at least model calibration/validation for single areas (if not for pasture composition) should be carried out, to make results more robust.

First part of the comment, validation of cropland. In the light of the previous comment, due to the lack of available data, carrying out a spatialised validation considering cropland development is not feasible at the moment. Furthermore, carrying out a validation by regions (NUTS2 or NUTS0), given the quality and discontinuity of the data available for some regions, is difficult, although this has been presented by some Authors (e.g. Lugato et al., 2017). The comparison we proposed here considers the average annual yield at European level for each crop under analysis, and during the historical period (1978-2004). As pointed out, when comparing all crop yields together, a good regression comes out due to the fact that the crops have different production levels between them. However, when analysing the yearly regression by crop over the time period explored, scores are less satisfying, with a more than likely "cloud" representation (as expected). Since in this work we are dealing with trends over EU, looking e.g. at the differences between the mean of the statistics and our simulation for each crop in the considered period, produced quite satisfactory results (14.22% on average, ranging between 1.57% for sugar beet and 28.60% for grain maize). We decided to add this figure anyway by removing the regression line and presenting the metrics per crop in the text (range, average, RMSE, MAE) and adding the table below in the supplementary material (Tab. S3). A representation of our results is also reported here below as boxplot (Figure R1) and, as suggested by the Reviewer, by single area, or NUT0 (most complete data available in Eurostat) in Figure R2.

Tab. S3. Statistics of the simulated crop yields compared with Eurostat in the period 1978-2004. Yields are reported as standard humidity.

crop	**MAE**	**RMSE**	**RRMSE**	**Mean** t DM ha^{-1}		**Minimum** t DM ha^{-1}		**Maximum** t DM ha^{-1}	
	t DM ha^{-1}	t DM ha^{-1}	%	**Simulated**	**Statistics**	**Simulated**	**Statistics**	**Simulated**	**Statistics**
Fodder Maize	2.21	2.97	27.1	10.66	10.95	5.41	5.54	15.37	15.09
Grain Maize	1.58	1.77	31.8	7.15	5.56	5.44	4.61	8.76	6.66
Oats	0.496	0.648	22.1	3.24	2.93	1.94	2.57	4.35	3.30
Potato	3.3	4.04	19.2	17.93	21.06	13.14	18.59	21.10	24.00
Pulses	0.387	0.462	18.2	2.21	2.54	1.90	2.18	2.58	3.01
Rapeseed	0.423	0.495	23.4	1.89	2.12	1.38	1.85	2.89	2.56
Barley	0.543	0.625	17.6	3.10	3.55	2.38	3.09	3.71	4.09
Soya	0.467	0.621	35	2.05	1.79	1.37	1.52	2.97	2.16
Sugar Beet	4.35	5.29	12.8	40.74	41.39	30.94	36.99	48.03	48.93
Sunflower	0.348	0.405	24.9	1.89	1.63	1.38	1.42	2.24	1.96
Rye	0.852	1.09	38.6	3.57	2.83	2.06	2.46	5.27	3.41
Wheat	0.894	1.05	25	5.02	4.21	3.59	3.47	6.16	4.83

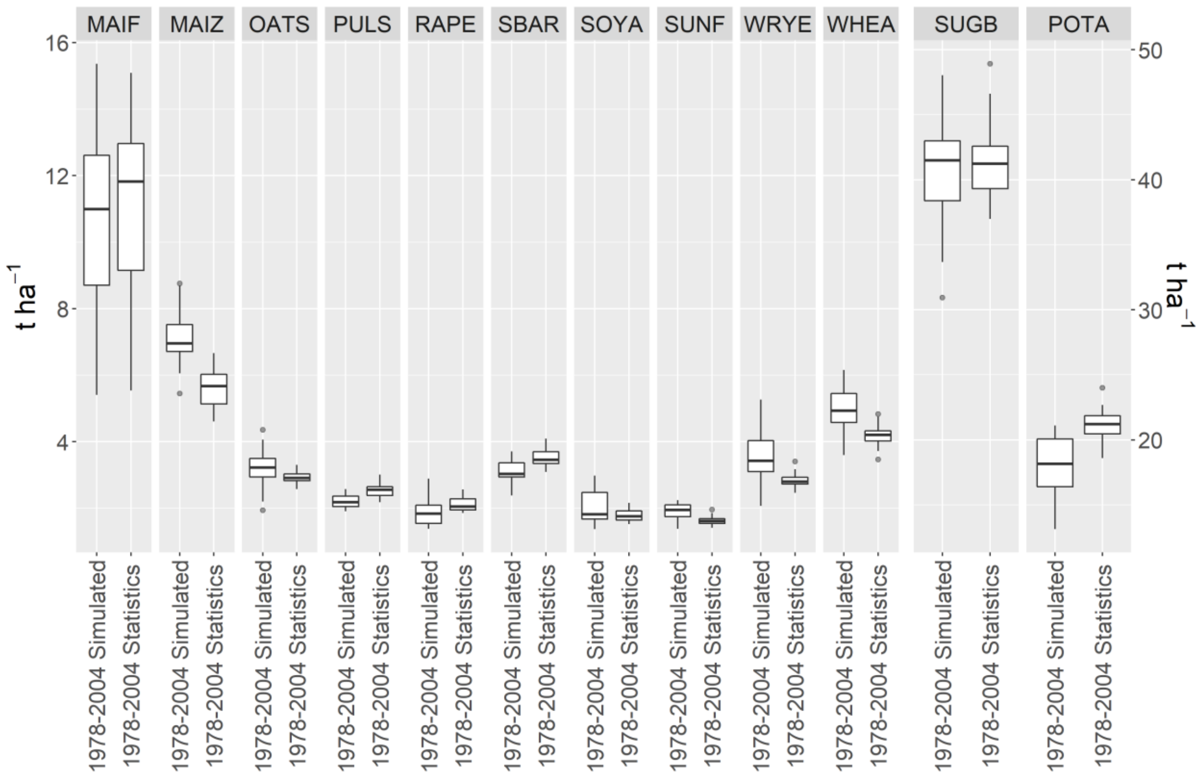

Figure R1. Difference between simulated and statistics (Eurostat) yields for the simulated crops in the 1978-2004 period. Crop names are reported as code names.

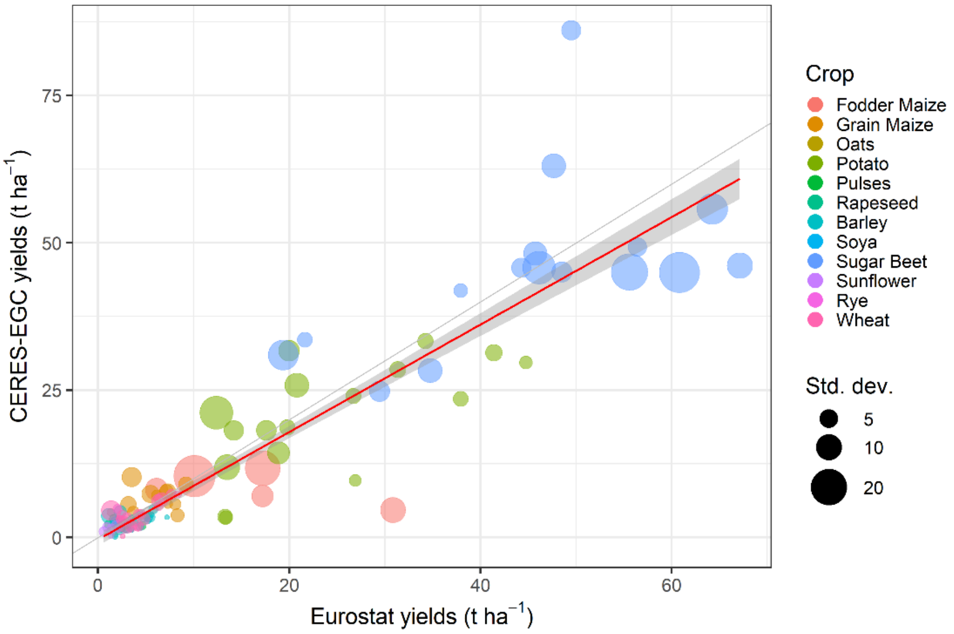

Figure R2. Difference between simulated and statistics (Eurostat) yields for the simulated crops in the 1978-2004 period. Each point represents the average 1978-2004 aggregated by country (NUTS0 level). Red line is the regression over the plotted points. This figure is reported only in this document.

Second part of the comment, validation of grasslands. The results presented by this study, as well reported in all the studies concerning grasslands in Europe (e.g. van Oijen et al., 2014, Chang et al., 2015; Chang et al., 2017; Blanke et al., 2018), suffer from the same problem of the overestimation of the Mediterranean area (Spain, Italy, Greece). This stems from the fact that the observed data over EU are scarce, and the existing databases (e.g. Eurostat) are incomplete. We decided to use the spatial analysis of Smit et al. (2008) based on regional, national and international census statistics for Europe, which are currently used as a reference also with the above-mentioned modelling estimations and other literature. For example, Chang et al. (2015) and Blanke et al. (2018) simulated higher potential productivity with, respectively, ORCHIDEE-GM and LPJ-GUESS-LUI than the productivity reported by Smit et al. (2008) and clearly declared that their estimations were decidedly far (above) compared to the Mediterranean area (Mediterranean Mountains, Mediterranean North, Mediterranean South). Although these results are not encouraging, they are in line with our outcomes. This overestimation is partly due to the fact that the models simulate the potential (maximum) productivity of grassland, whereas Eurostat productivities are based on actual harvest data. Although these estimations biased, some study presented also projected scenarios into the future (Chang et al., 2017; Blanke et al., 2018). Finally, to strength our findings, in our study we tried to compare the results with the available measured data over EU (Hörtnagl et al., 2018; Viuchard et al., 2007; Soussana et al., 2007; Merbold et al., 2017) with reliable results.

Aware that the collection of data across European countries need to be more consistent and standardised to improve the quality of European grassland productivity and land use data, we decided to address better this point in the §4.5 chapter concerning the uncertainty and the limits of this work, to avoid any misinterpretation. Since we do not dispose of the Smit et al.

(2008) database, we based our comparison with the results present in their publication (average per area in the period considered), thus we are in measure to provide the evaluation which is already been provided in the manuscript and in Figure 1.

4. I appreciate the wide analysis done by authors; however, the above-described issues make the level of confidence of these results very low. Discussion section do not address this high level of uncertainty and only report the agreement in the impacts with other studies. This information is quite negligible if not accompanied by a strong model performance in the magnitude of the results. Simulated dynamics are found expected since driven by common algorithms (i.e., GDD for crop growth), but robust information about the expected change need to be provided. Whilst crop data may be improved, I'm quite concerned about pasture dynamics which need to be adequately addressed through a more consistent approach since, at this time they cannot be accepted as here proposed.

Based on the literature produced and the data available, we find that our work, although different in terms of input data and less extensive in terms of management possibilities, has a level of confidence comparable to the previous cited publications on grassland modelling (e.g. Chang et a., 2015, 2017; Blanke et al., 2018). We aimed to show tendencies related to future climate change in order to improve our understanding. Results are discussed and an overall uncertainty of the work is added (new chapter), starting from the input data and ending with their interpretation. As described above, this also applies to crops.

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