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Earth System Dynamics Discussions

Interactive comment on "Climate change imposed limitations on potential food production" *by* Philipp de Vrese et al.

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Climate-food dynamics

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Climate change imposed limitations on potential food production: Reply to reviewer 2

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Before going into detail about the changes done to the manuscript, we would like to sincerely thank the referees for taking the time to help us improve our manuscript, pointing out shortcomings and providing possible solutions for these. We think that especially the additional information on the issue of nutrient availability contributed to the discussion section, while a more detailed discussion on the RCPs and on the uncertainties in the soil characteristics improved the result and the method section. We structured our reply to the reviewer's comments as follows. At first we repeat the **referees point of criticism** in bold letters, which is followed by a reply which is not included in the manuscript (in plain letters), and finally we give the *parts in the manuscript that were altered* in italics.

2.1) In my opinion the title of the paper is not well chosen because speaking about limits of food production the study should address more comprehensive

view also including other than biophysical constrains. More straightforward title reflecting the main highlight of the study which is cropland expansion and sustainable world population would better reflect the content of the study.

To make the title more precise, especially with respect to being an investigation of biophysical mechanisms, we changed it to the following:

"Exploring the biogeophysical limits of global food production under different climate change scenarios"

2.2) Comparison of selected climate variables (CO2 concentration, surface temperature, precipitation, and water deficit) to original ESM would nicely emphasize the importance of the newly introduced crop management and water management modules.

We fully agree with the reviewer that a further analysis of the climate impacts of the simulated cropland expansion (especially irrigated) would add additional insights to the manuscript. However, we think that the comparison to standard MPI-ESM simulations should not stand by itself but requires an extensive discussion, which is beyond the scope of this paper. This is especially the case as the present setup is not only new in the MPI-ESM but has also not been investigated by any other modelling group (an extreme scenario that is interactively constrained by water and land availability). There is an ongoing study that targets the possible importance of irrigation as a geo-engineering tool, and we plan to comprehensibly discuss the climate impacts in the present simulations as a part of this study.

2.3) How can be competition with crops produced for energy taken into account?

Unfortunately, the impact of this competition can not be fully evaluated using the present model setup. As herbaceous biomass plantations would have a very distinct effect on climate, we would have to adapt the model to also represent them explicitly. In the method section (Translation of cropland productivity into the sustainable population size) we explained that the assumption of a constant ratio between food and energy crops constitutes a possible oversimplification.

We also did not account for potential changes in the ratio of food to energy crops. Here, studies indicate that an increased demand for biofuels could result in a larger fraction of agricultural areas being dedicated to growing energy crops in the future (Berndes et al., 2003; SIMS et al., 2006; Johansson and Azar, 2007; Rathmann et al., 2010; Harvey and Pilgrim, 2011). As a first order effect, it can be assumed that the decrease in the yield of food crops is proportional to the increase in the share of energy crops. However, it is very unlikely that the same crops will be used to produce food and energy, as is the predominant practice at the moment. On the long term, it is more likely that dedicated plants, especially C4 grasses, would be used to produce energy (Heaton et al., 2008). Increasing the share of these plants would have an effect on climate that is different to the expansion of traditional (mostly C3) crops. Consequently, capturing the full effect of an increased demand for energy crops, requires their explicit representation in the model and further assumptions about the respective future demand.

2.4) The biophysical assumptions on CO2 fertilization effect are only valid if sufficient amount of nutrients is supplied to the crops which is not case in most developing parts of the world. Yet making sense from the bio-physical perspective the projected cropland expansion (or loss) should be also examined in the socio-economic development concept.

It is true that fertilizer availability is an issue especially for developing countries but we fear that going into a detailed discussion on this problem on a regional or even national level goes beyond the scope of this study. Nonetheless, we fully agree with the reviewer that nutrient limitations are a key factor which we may not have acknowledged sufficiently in our discussion of the results. In order to discuss the nutrient supply as a global scale issue, we integrated the following aspects into the discussion section.

In addition to climate effects, weed and insect pests as well as increasing nutrient requirements are expected to reduce the strength of the CFE (Tubiello et al., 2007). Here, constraints due to fertilizer availability present one of the key limiting factors. For example, Rosenzweig et al. (2014) investigated the crop yield response for the RCP8.5 scenario as simulated with different global gridded crop models. The study showed that yields for the major crop types predominantly increase if no explicit nitrogen limitation was accounted for. However, when nitrogen limitations are introduced and fertilizer application is restricted to present day rates, the effect of CO2 fertilisation is greatly reduced and all major types exhibit a decline in crop yields throughout the low and parts of the mid latitudes (Rosenzweig et al., 2014). In principle di-nitrogen gas provides an unlimited source of nitrogen. However, nitrogen fixation, i.e. the process by which atmospheric nitrogen is made available for plants, requires high energy inputs. At present, the share of fertilizer production in the global energy consumption is estimated to be around 1% (Vance, 2001; Dawson and Hilton, 2011), and the fertilizer requirements as proposed in this study could easily increase this share to more than 5%. In case of phosphorus the situation is more difficult as it is, effectively, a non-renewable resource and our supply stems from mines which are located in only a few countries. The size of the phosphate rock deposits is highly uncertain and by far the largest deposits have only since recent been included when taking stock. Given our current use of phosphorus, these known resources would last for

the next 400 - 800 years (Cordell et al., 2009; Dawson and Hilton, 2011). With the increase in fertilizer demand, as proposed by this study, the deposits of phosphate rock may not last long beyond the investigated period. Industrial agriculture, even on the present-day scale, is not possible without phosphorus fertilization and productivity would quickly diminish to the level prior to the agricultural revolutions of the 19th and 20th century if our resources are exhausted. Hence, the future food supply will strongly depend on how much energy is available for the production of fertilizers and how effectively nutrients can be recycled.

But even if sufficient fertilizers could be provided, this would increase other problems related to their application. The present-day fertilizer use already has strong detrimental impacts on the ecosystems in certain regions, where an excess of the respective elements can leave entire lakes, rivers and coastal stretches uninhabitable to plants and animals (Vitousek et al., 1997; Smith, 2003; Rockström et al., 2009). As a consequence, it has been suggested that the extent of croplands should not surpass 15% of the global ice-free land surface (Rockström et al., 2009; Steffen et al., 2015). Any further expansion could bring the planet to a tipping point, e.g due to hypertrophication resulting from increased use of fertilizers and the loss of biodiversity. This would mean that we have to retain agricultural expansion far below the limits set by climatic conditions. Limiting croplands to 15% of the global ice-free land surface, would roughly halve the potential cropland area as estimated by this study, i.e. about a third of the ice-free land surface, resulting in similar decreases in crop yields and food security. Additionally, the study's assumption that per capita food requirements will remain at present day levels may also contribute to an overestimation of the level of food security. Dietary shifts are expected to double global food requirements by 2050 while the population is only expected to increase to about 9bn (Godfray et al., 2010). It is highly doubtful whether this dietary shift and population increase could be sustained without expanding the cultivated areas beyond the safe limit of 15%. Here, our results indicate that only a very strong CFE could lead to the necessary increase in crop *yields. Additionally, it would require shifting cultivated areas to the most productive regions, mostly in sub-Saharan Africa, South America and South East Asia, and to provide an almost perfect irrigation system (Fig. 7).*

2.5 a) Possible gains of cropland areas in marginal areas could be not suitable for intensifications and/or not accessible or effective from the socio-economic or geopolitical point of view. Not mentioning this explicitly could lead to wrong message and too optimistic estimates of global food production and carrying capacity for growing worldwide population in the future.

To not run the risk of presenting an overly optimistic outlook, we added the following passage to the description of the soil constraints:

Finally, it should be noted that the information on soil constraints merely provides an upper bound to the cultivable area in the present idealized scenarios but not necessarily to potentials in the real world. Especially in marginal areas, the cost of cultivation, e.g. due to the required irrigation related infrastructure or fertilizer input, may mean that agricultural intensification is not feasible under socio-economic considerations, even though it may be technically possible.

2.5 b) ... In this sense the SSPs should be at least briefly discussed in the context of the presented study not just compared to existing official population estimates released by UN.

To provide some more information on the RCPs, we describe the assumptions made with respect to population development, future energy demand and the mix of energy carriers. Furthermore, we contrast the underlying land-use change scenarios with our

own findings.

The RCPs are consistent with distinct socio-economic pathways that differ strongly with respect to future energy demand and the mix of energy carriers. Included are assumptions about resource availability and climate policies, which determine the contribution of fossil fuels to the energy mix, as well as assumptions about the population development, which strongly affects future energy demands. Additionally, the scenarios take into account different land-cover and land-use change projections which reflect future food and energy demands as well as policies with respect to reforestation (Meinshausen et al., 2011; van Vuuren et al., 2011). RCP2.6 and RCP4.5 present intermediate scenarios with ambitious emission reductions, which in case of RCP2.6 even include a decline in the use of oil. For RCP2.6 and RCP4.5 the population development corresponds to UN projections assuming a low to medium fertility and life expectancy in the future (UN, 2004, 2015a,b). In contrast, RCP8.5 presents a highly energy-intensive scenario without the implementation of any climate policies. The high energy demand in this scenario partly results from a strong population growth, which corresponds to a medium to high population trajectory in the UN development scenarios. In order to estimate the level of food security for a given combination of RCP and population development scenario, the simulated K_{hum} can be compared to the population levels proposed by the UN scenarios. Here, the simulations indicate that the ability to sustain future populations depends heavily on the strength of the CFE. When assuming the full benefits, only the population of the high-fertility (and life-expectancy) scenario may become unsustainable, i.e the respective population trend surpasses K_{hum} as simulated for RCP2.6 and RCP4.5, and that only if protected areas are maintained (Fig. 5a,b). However, without the CFE the food requirements resulting from the high-fertility scenario can not be met by any simulated supply, even if protected areas are converted into croplands (Fig. 5c,d). Also the population of the medium-fertility scenario is very close to K_{hum}, indicating that we may need to cultivate almost all non-protected areas and to have a near-perfect system for irrigation in order *to meet the future food requirements of this scenario. Here, our findings contradict the RCP's underlying scenarios. These assume that the population increase in RCP8.5 could be sustained without increasing the cropland area beyond $20 \cdot 10^6 km^2$, while the population increase in RCP4.5 could even be met with a substantial decline in the cultivated area (Meinshausen et al., 2011; van Vuuren et al., 2011).*

2.6) Food production is simulated mostly as a function of water availability for the plants driven mostly by the climate, but locally affected by soil water holding capacity and soil water balance. There is no information on the source of soil data used in simulations nor the discussions on possible effects of soil variability on the crop yield production (c.f. e.g. Folberth et al. 2016, NatCom).

The uncertainty in soil parameters is an issue that is not only relevant with respect to crop yields but also for climate simulations, and at present we are participating in the Soil Parameter Model Intercomparison Project (SP-MIP), led by Lukas Gudmundsson and Mathias Cuntz, to better understand to which extent the large spread among LSMs with respect to water-balance variables is related to soil model parameters. For simulated crop yields the problem is potentially larger because also subgrid scale variability becomes an important factor as, on the subgrid-scale, there should be a correlation between presence of crops and favourable soil characteristics. We tried to point out the respective shortcomings by including the following passage into the description of the soil constraints:

The soil constraints were used to determine the maximum grid box fraction suitable for farming but they did not have a direct impact on the distribution of the simulated soil characteristics. This is a major limitation of the model, as the part of the grid box that is able to support crops should be represented by more favourable soil characteristics than the fraction that is affected by soil constraints. However, as the

MPI-ESM is a global model, in which the soil characteristics are described on the large scale, subgrid-scale variability can not be taken into account consistently. The effect of soil variability within a grid box is only taken into account for the calculation of surface runoff and infiltration (Düllmenil and Tondini, 1992). The soil data used in the MPI-ESM are based on adjusted FAO soil type and soil profile datasets and an overview over the derivation of soil parameters can be found in Hagemann and Stacke (2015). With this parameter set, the MPI-ESM captures the land surface water and energy fluxes well (Hagemann et al., 2013) but it should be noted that many of the soil parameters are only poorly constrained and the impact of the respective uncertainty is not well understood (Orth et al., 2016). Here, studies have shown that the the large uncertainty in global soil data does not only introduces substantial uncertainties with respect to numercial weather prediction and climate simulations, but also with respect to simulated crop yields (Grassini et al., 2015; Folberth et al., 2016; Hoffmann et al., 2016; Montzka et al., 2017).

2.7) Minor limitation of the approach is also oversimplification of biophysical response of the crops which can be better addressed by other, more specific models ? a comparison of the simulated potential yields with other global gridded crop models would make the modelling outcomes more reliable.

It is quite difficult to compare our results to other models as they are substantially impacted by our ability to include climate feedbacks and the maximization of irrigation. The only valid comparison that can be made is for yields in the simulation without irrigation (RF45*) and that only in regions that, at present, are dominated by rainfed crops. In these regions, the simulated yield decline of about 5%/K is actually in good agreement with other studies which we included in the discussion section (see also reviewer 1; point 1.4 b).

In the study, the crop's general response to changes in climate agrees well with estimates of other studies (Lobell et al., 2011; Asseng et al., 2014; Challinor et al., 2014). When omitting the CFE and effects of irrigation (RF45), regions that are presently dominated by rainfed agriculture exhibit an average decline in yield per area of about 5 % per K temperature increase, i.e. in grid boxes where 5 % of the area or more were covered by crops in the year 2005 and less than a third of this cropland area was irrigated, a temperature rise of about 2.6 K caused an average reduction in crop yields per area of about 12 %. The yield response to changes in temperature is strongly affected by the study's management assumptions and, in the same regions, the average yield per area increases by about 2 % per K temperature increase, when irrigation is maximized within sustainable limits (IR45*), i.e. for the temperature rise of about 2.1 K we estimated an average increase in crop yields per area of about 5 %. Hence, the assumptions made with respect to future irrigation, including the representation of the resulting climate feedbacks, are one of the reasons why the development of global crop yields under the RCP scenarios is much more positive than in many other studies (Guoju et al., 2005).*

Nonetheless, representing crops by just two types is a strong oversimplification and we changed the respective manuscript part to the following:

As mentioned above, in JSBACH crops are not represented by individual species such as maize, wheat or soy, but by two functional types (C3 and C4 crops). This leads to an oversimplification of the biophysical response of crops and presents a strong limitation of the model in comparison to current day crop models. However, it is the common practice in Earth-System modelling.

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