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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 1

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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 the manuscript benefited especially from the additional information in the introductory section, the discussion on the simulated CO_2 fertilization effect and the additional comparison to other studies. 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.

1.1) A main point of concern with the current manuscript is that it provides little information on the methods and scenario assumptions, unless one reads the Methods section. The Introduction ends with a short summary but then the

Results immediately follow - more information is required at this point because it is crucial for readers' understanding and interpretation of the findings, and to make transparent the (partly strong) scenario assumptions. I suggest to at least add the following information at this place: what is the spatial/temporal resolution and the forcing of the model (incl. climate, CO2, land use/protected areas); what are the environmental flow requirements about; how is area converted into (future) food supply; how is it possible that areas decline, what is the criterion for that.

Due to the description of the new schemes, the methods section became rather long and we were hoping to avoid the more traditional structure in which it follows the introductory section. We are grateful to the reviewer for pointing out the missing details, which allows us to provide the reader with a good overview without having to read the entire methods section. To include the additional information, we changed the introduction to the following:

In the approach, the spatial extent of cultivated areas is modelled as a function of climatic conditions as well as the agricultural water supply. In regions where conditions allow for at least a minimum productivity, i.e. the crops' net primary productivity (NPP) corresponds to a yield of at least $\approx 250\, t\, km^{-2}$*(canopy) year*$^{-1}$*, the cultivated area is extended incrementally until all cultivable areas are occupied, i.e. the land not limited by soil or terrain constraints. In regions in which the NPP falls below this threshold, the area under crops declines. The NPP was also used to estimate the potential food production, by assuming that the changes in crop yields are proportional to changes in the plants' NPP. To estimate the potential food production on a hydrologically sustainable basis, future water withdrawals are limited to the fraction of renewable fresh water which exceeds environmental requirements. Here, it is assumed that about a third of the long-term mean flow is required to ensure ecological stability and may*

not be withdrawn (Pastor et al., 2014). Water for irrigation is removed from the river network and stored in a dedicated reservoir. When required, the water is applied to the soil, from where it evaporates, is taken up by plants and transpired or returned to the river via subsurface runoff (for more details on the methodology see Sec. 4). Together with the changes in the surface-atmosphere exchange of energy and moisture that result from alterations of the surface characteristics, this closes the feedback loop between land-use and climate (Fig. 2).

We used this adapted model to investigate the climate-agriculture dynamics during the 21st century that result from the maximization of the cropland area under different atmospheric green house gas (GHG) concentration scenarios (Fig. 3b, Tab. 1 and Sec. 4). The simulations cover the period 1995 - 2114 and were forced according to three representative concentration pathways (RCP, Meinshausen et al. 2011; van Vuuren et al. 2011) that assume a peak and a subsequent decline of emissions until 2020 (RCP2.6) and 2040 (RCP4.5) as well as an ongoing increase in emissions (RCP8.5). They use a temporal resolution of 450 seconds, a horizontal resolution of T63 (1.9° $\times$ *1.9°) and vertical resolution of 47 atmospheric model levels.*

To clarify which areas are considered to be under protection we added the following:

By excluding these areas from the analysis, i.e. areas placed under protection (Juffe-Bignoli et al., 2014; UN, 2016) and those covered by tropical forests (as of 2005), the cultivated area in 2100 is reduced by roughly 15% (Sec. 4 and Fig. S2).

With respect to the "climate forcing" we did not alter the manuscript, as we performed fully coupled simulations (land, ocean, atmosphere) and, besides the green house gas concentrations, the only external forcing is given by the prescribed orbital parameters.

1.2) Furthermore, a clear research question should be formulated.

Even though we did not formulate it as a question, we tried to present the target of the investigation more concisely:

The focus of this investigation is on the global crop yields that are achievable under future climate conditions and, in the following analysis, we will show the potential expansion of cultivated areas, the changes in global yields and how these relate to future food security. The effects of changes in irrigated and rainfed cropland area on climate will only be discussed very briefly as their detailed analysis goes beyond the scope of this study.

1.3) Related to that, parts of the Results section should be formulated more carefully. For example, on page 3 it is stated that "almost three quarters of all cultivable land could be farmed by the beginning of the next century". Also on page 7 line 16: is a "vast increase in food imports" really the only way out, can such a claim be supported by other literature? Please make always sure that this is only in your very idealized simulation, which explores some upper potentials based on biophysical processes and land-climate feedbacks but not on socially (and technologically?) feasible potentials.

We edited the sentence on page 3 and in the revised version it starts by stating that the cropland expansion pertains to the simulations.

In the simulations, the cropland area can be tripled to roughly 38 - 42$\cdot 10^6 km^2$*, and*

almost three quarters of all cultivable land can be farmed by the beginning of the next century (Fig. 3a, Tab. 1)

It is true that the study uses some simplifying assumptions which could turn out to be overly pessimistic. However, we also neglected certain constraints which could become decisive limitations in the real world. To maintain a balance between admitting that the study may underestimated crop yields (i.e. a "vast increase in food imports" is not required) and not presenting an overly optimistic perspective, we included the following part on page 7.

It is possible that the present study underestimates the potential food production especially as possible technical solutions, such as better adapted crops or large scale desalination efforts, are not being accounted for. On the other hand, the study neglects important constraints, e.g. resulting from fertilizer availability or the limited water-use efficiency of irrigation systems. As, in reality, these will strongly affect future crop yields, the present idealized scenario may likely provide an overly optimistic outlook. This is especially the case for the simulations that assume a large increase in GHG concentrations, i.e. RCP4.5 and RCP8.5, and account for the full benefits of the CFE.

It wasn't our intention to present the results as pertaining to real-world potentials. In order to make sure that they are understood as merely idealized scenarios, we included the following part at the end of the introductory section.

It should be noted that the present framework targets biogeophysical feedbacks, with a special focus on the hydrological cycle, while other important limitations arising due to social, political, economic and technological factors are being neglected. Therefore, the below results merely pertain to the development of cropland areas and yields in an *idealized scenario and not necessarily to real-world potentials, the latter of which may be much more constrained by e.g fertilizer availability, cost of transport and irrigation related infrastructure, dietary shifts and the competition with energy crops.*

1.4 a) The Discussion is very short (with the two first paragraphs being only an extension of the Results) and rather weak. Here I would expect a critical reflection of scenario assumptions including more literature references on 1) how does the CO2 effect in your model, which has such a very strong impact on the results (increasing K_hum by up to 12 billion!), relate to findings from other studies; ...

We agree that the CFE should have been discussed in more detail. We hope to correct this by including the below discussion:

Another reason for the high simulated yields, is the model's comparativly strong CFE. Many studies have investigated the effect of increasing atmospheric CO_2 concentrations on vegetation (Tubiello et al., 2007). These indicate that there is a substantial photosynthetic response to increasing CO_2 levels, i.e. under optimal conditions, doubling the present day CO_2 concentrations leads to an increase in photosynthesis of 30 % - 50 % for C3 and 10 % - 25 % for C4 plants. With respect to crop yields, the existing studies exhibit large uncertainties and strong variations between crop types and regions. For CO_2 increases similar to the ones assumed by the RCP4.5 scenario, the estimates range from a 2.5 % to a 25 % yield increase per 100 ppmv increase in CO_2 (Amthor, 2001; Tubiello et al., 2007; Ainsworth et al., 2008; Asseng et al., 2013; McGrath and Lobell, 2013). In the RCP8.5 scenario, the atmospheric CO_2 concentrations towards the end of the century exceed 1000 ppmv. At these levels, the benefits due to additional CO_2 are much smaller as even C3 crops are close to (or have already reached) their saturation level. For the rise in CO_2

concentrations assumed by this scenario the average yield increase is expected to be below 6 % - 8 % per 100 ppmv increase in CO_2 (Parry, 1990; Amthor, 2001; Ainsworth and Rogers, 2007; Ainsworth and McGrath, 2010). In comparison to these studies, which predominantly consider yield increases under optimal conditions, the MPI-ESM simulates a very strong CFE (approximated by the productivity difference between the simulations with and those without increasing the plant-available CO_2). In regions that are being farmed at present (grid boxes in which 5 % of the area or more were covered by crops in the year 2005), the simulations for the RCP4.5 scenario that account for irrigation exhibit an average increase in yield per area of about 18% per 100 ppmv increase in CO_2. Owing to the higher temperatures and lower water availability, the simulated strength of the CFE is slightly lower, i.e. about 14% per 100 ppmv increase in CO_2, when irrigation is not represented. For the RCP8.5 scenario, our simulations showed an increase of about 10 % per 100 ppmv increase in CO_2. These values place the CFE simulated with the MPI-ESM at the higher end of the range of current estimates, in case of the RCP8.5 scenario even exceeding them, indicating that the model overestimates the strength of the CFE and the resulting crop yields.

1.4 b) ... 2) what are the crop management assumptions in your study, which is important relative to other studies which use specific increases in management which in turn affects the crop area.

Possibly the most important assumption is that future irrigation is being maximized within sustainable limits. On one hand this directly increases the water availability, on the other hand it leads to climatic conditions that are much more favourable for plants, i.e. lower temperatures and increased precipitation. When removing these effects, i.e. focusing on the simulation without irrigation and on regions that are dominated by rainfed agriculture, our results actually agree well with other studies. In the manuscript, we included the following part into the discussion section:

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).*

1.5) The title is quite general and does not well reflect that it is about a global modelling study of theoretical maximum potentials, thus I suggest to adapt it in this regard.

We changed the title to the following (see also reviewer 2; point 2.1):

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

1.6 a) Abstract: Some more crucial information should be added, that is, which (climate) scenario runs you analyzed,

We extended the abstract to include the following information:

For three green house gas concentration scenarios (RCP2.6,RCP4.5,RCP8.5), we show that the total cropland area could be extended substantially throughout the 21st century, especially in South America and sub-Saharan Africa, where the rising water demand resulting from increasing temperatures can largely be met by increasing precipitation and irrigation rates.

1.6 b) ... why areas are to be abandoned in some of the simulations, ...

When accounting for the CO_2 fertilization effect, only few agricultural areas have to be abandoned owing to declines in productivity, while increasing temperatures allow to expand croplands even into high northern latitudes.

1.6 c) ... and what are the "most optimistic assumptions" mentioned in the final words.

Admittedly, "optimistic" may have been a poor choice of words. We changed the formulation to the following:

For certain regions the situation is even more concerning and guaranteeing food security in dry areas in Northern Africa, the Middle East and South Asia will become increasingly difficult, even for the idealized scenarios investigated in this study.

1.7) The first paragraph of the results is partly Methods, partly self-evident, it could be deleted.

With restructuring the introductory section to include the additional details, this part has been removed from the results section.

1.8) Does the CO2 fertilisation effect apply to both crops and natural vegetation?

The CFE applies to managed as well as to natural vegetation and by limiting the plant-available CO_2 to 380 ppmv also the natural vegetation is affected.

1.9 a) Page 4 first paragraph: What do you mean, "without requiring any previous changes"?

We ment to say that the climatic conditions, i.e. temperature and precipitation, are already suitable for growing crops at the beginning of the simulation. In order to clarify this, we edited the sentence to the following:

Wide areas could be cultivated without requiring any changes in the conditions, i.e. temperatures and precipitation rates are already in a favourable range at the beginning of the century, and the largest potential for expansion is given in latitudinal zones in which crops are already being grown (Fig. 3a; right panel).

1.9 b) Same paragraph and at other places: I think the term "sustainable" is not correctly used here, it is misleading; rather use "achievable"?

We are not entirely sure that "achievable" correctly describes the simulated irrigation withdrawals, as it gives the impression that really all available water is being used. We designed the water management scheme in a way that the environmental flow is being ensured. Thus, from an ecological perspective the simulated irrigation is sustainable, and we did not change the manuscript.

1.10 a) Page 4 third paragraph: It is unclear whether you here talk about global sums only or about regional patterns (i.e. is increased demand met globally or in the very regions); in any case more focus and examples on specific regions are needed.

Indeed, it was bit unclear that we were talking about the general behaviour on the land surface. To clarify this, we edited this paragraph (see below). For the RCP4.5 and RCP8.5 it is valid to omit a more detailed regional analysis as it is really only very few grid boxes whose behaviour deviates from the description. For RCP2.6, however, there are a few areas in which the increased water demand can not be met, which we added to the manuscript.

The scenarios that exhibit a strong temperature rise also show a substantial increase in precipitation over land (Fig. 3d). For RCP4.5 (IR45) mean precipitation rates increase by up to 20 mm year^{-1} and in IR85 they increase by about 60 mm year^{-1}, which amounts to more than 8% of the terrestrial precipitation as of 2005. Increased precipitation rates do not only reduce the water stress for rainfed crops, but between 2025 and 2100 they also increase the water available for irrigation; globally by roughly 500 km^{3}year^{-1}, for IR45, and by almost 2000 km^{3}year^{-1} for IR85 (Fig. 3e). As a consequence, the increased water demand of *irrigated and rainfed crops resulting from higher temperatures can be met to the extent that, after 2025, there are only very few areas in the world in which farming becomes unsustainable. This however is only the case when fully accounting for the potential benefits due to the CO_2 fertilization effect (CFE; see below). For the simulations with only a small increase in GHG concentrations (IR26) there is no permanent increase in precipitation, i.e. after a peak in the 2040s the rates decline to their initial levels, while the average temperature at the land surface increases by* $\approx$ $1K.Here, theplant'sincreasingwaterrequirementscannotbemeteverywhereandinsomedryre$

1.10 b) Same page, next paragraph: I do not understand why "the results highlight the importance...".

Again, this may not have been an ideal choice of words. We changed the paragraph to:

The results show that future climate is substantially impacted by the maximization of irrigation within sustainable limits.

1.11 a) Page 5 first paragraph: 20% or 0.5K temperature increase is high ? especially if that is a global value? What particular scenario does this relate to, i.e. how large an area is assumed to be irrigated and where?

We estimated the impact of irrigation as the difference between the RCP4.5 simulations with (IR45) and without (RF45) irrigation. With about 0.5 K, the temperature effect due to irrigation is indeed very large, but so is the irrigated area. In the IR45 simulation the irrigated area is more than quadrupled from 2% to about 8% of the global land surface (as compared to the reference simulation). Here, Fig. S4 in the supplementary material gives a good overview of how the irrigated area develops

when it is being maximized within sustainable limits (even though it pertains to the year 2025 and irrigation still increases afterwards). In the text we clarified that the reduced temperature refers to the effects of irrigation with respect to the RCP4.5 scenario:

Furthermore, for the RCP4.5 scenario, irrigation reduces the simulated 21st-century temperature increase by almost 20% ($\approx$ 0.5 K averaged over the global land surface; Fig. 3c), and in irrigated regions the effect can amount to several K.

1.11 b) I also think it is not correct to express temperature changes in %.

Due to the arbitrary zero point of the common temperature scales (F & C) changes in temperature should indeed not be given in %, e.g. global surface temperature changes by 5%. However, in the manuscript we do not have the zero point issue as we merely give the fraction by which a certain temperature increase is reduced, which, to the best of our knowledge, is a valid formulation.

1.12 a) Page 6 line 10: Please avoid such a statement if possible, as it appears to "recommend" RCP8.5 because it increases food production; ...

We made the respective formulation more careful as we did not want to give the impression of promoting the RCP8.5 scenario.

Here, the results seem to suggest that the high concentration trajectory is favourable with respect to food production, however, this is only the case if the CFE is as efficient as simulated by the MPI-ESM.

1.12 b) ... this is also in contrast to many climate change impact studies that suggest strong declines in yields - which need to be cited here (or rather in an extended Discussion).

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 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).*

1.12 c) Same page lines 21-23: I do not understand this, safe climatic range for food ... ?

To clarify, we changed the formulation to:

Given the high level of uncertainty connected to the CFE, the range of climatic conditions that are favourable for food production is likely limited to the conditions resulting from the RCP4.5 scenario.

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