Interactive comment on "The relevance of uncertainty in future crop production for mitigation strategy planning" by K. Frieler et al.

Anonymous Referee #2

In their analysis the authors apply different crop growth models to assess uncertainties of crop production on current agricultural land and for a land use scenario under a range of climate projections and agricultural management options (in terms of levels of crop irrigation). Additionally they apply a set of bio-geochemical models to analyze the carbon losses due to the projected land-use change. The authors present an interesting study design which from my point of view is inconsistent in parts. Also the paper itself is hard to follow and lacks detail to fully understand how the analysis was done.

Altogether I think the paper needs major revisions.

R2.1 The title of the paper refers to mitigation strategy planning. The authors need to explain in more detail how such a planning process might look like and how exactly the addressed uncertainties should be incorporated into it (who is responsible for this global planning process? Which level of detail does it have etc.).

Answer:

We hope that the full revision of the introduction provides a better explanation of the concept. Starting from the conceptual Figure 1 it now also includes a more detailed description of a possible implementation based on multi-model cross-sectorally consistent impact projections. We consider it as our responsibility as scientists to provide the necessary information allowing for robust decisions regarding future mitigation planning and ensuring of food security while the decisions themselves have to be taken by the societies.

R2.2 In the introduction the authors describe a risk-assessment framework that applies pdfs. Here I would expect a broader overview of possible approaches to quantify risks and the potential role of models within those frameworks. The description of the particular framework used within the study should be moved to the "data and methods" section. It should also be stressed that it is applied only in a qualitative manner ("... shifts the red uncertainty distribution to the left.").

Answer:

We would like to introduce the framework as a quite general concept for decision making under impact model uncertainties. It is not a method we finally apply to the data. Therefore we would like to keep it in the introduction. We have changed the naming of the concept from "risk-assessment framework" to "probabilistic decision framework" as it does not refer to the classical concept of risk as "magnitude of damage x probability of its occurrence".

While Figure 1 only describes the general concept in a highly simplified situation we have now added a paragraph describing the concrete implementation of the concept based on multi-model impact simulations. In general given appropriate model simulations the framework allows for a quantitative assessment of different management options. However in this paper it is not fully applied but the following analysis of the ISI-MIP simulations underlines the necessity of an integrative decision framework accounting for impact model uncertainties. We hope that the modified introduction clarifies this scope of the paper.

R2.3 Moreover I think the equation N = T – F is far too simple as other ecosystem services are not included. If maximizing carbon storage is the only goal this should be stated clearly and needs to be discussed in more detail.

Answer:
In the current description of the framework we focus on carbon storage and bioenergy production as two "demands" that have to be fulfilled on the remaining land area assuming that food demand will always be fulfilled. We focus on these two aspects because these demands can be expressed in a straight forward quantitative manner. Other ecosystem serves could of course be added on the demand side given that they can be expressed in a quantitative manner. We have added an associated statement to the introduction:

"Similarly, the land area required to meet a certain climate mitigation target depends on: 1) the amount of energy to be produced as bio-energy and the required amount of natural carbon sinks, 2) human decisions determining the intensity of bio-energy production per land area, and 3) bio-physical constraints regarding the production of bio-energy per land area and potential losses of natural carbon sinks under climate change. We consider climate protection by bio-energy production and carbon storage in natural vegetation as examples of additional constraints on land-use (LU) that are relatively straightforward to quantify. However, other ecosystem services could impose further constraints that could be integrated if it is also possible to describe them in a quantitative manner based on available model outputs or external sources. For example, Eitelberg et al., 2015 have shown that different assumptions with regard to protection of natural areas can lead to a large variation of estimates of available crop land."

R2.4 Also the last paragraph of the introduction should be moved to the following section.

Answer:
We have moved it to section 3.3 "Impact model simulations". Now the text reads:

"The quantity projected differs from model to model, ranging from yields constrained by current management deficiencies to potential yields under effectively unconstrained nutrient supply (Table 1 and Table S1 of the SI). Therefore, we only compare relative changes in global production to relative changes in demand. Since simulated yield changes may strongly depend on, for example, the assumed level of fertilizer input in the reference period, we consider this aspect as a critical restriction. In this way, the analysis presented here is an illustration of how the proposed decision framework could be filled, rather than a quantitative assessment."

R2.5 The description of the input data in section 2 is incomplete. E.g. MIRCA is not even mentioned (which is the reference year for the base cropping pattern? 2005?). In this context also the uncertainties due to the spatial data sets should be shortly addressed later in the discussion. The description of the impact models is incomplete, too. The GGCMS should be listed in a table in the main text. A short description of the hydrology models and bio-geochemical models and how they are applied within the study context should be added.

Answer:
We have added these elements to the Data and Methods section. MIRCA is now introduced in section 3.2 "LU patterns and demand":

"As present day reference for agricultural LU pattern we apply the MIRCA2000 irrigated and rainfed crop areas (Portmann et al., 2010). They describe harvested areas as a fraction of each grid cell. The patterns are considered to be representative for 1998-2002. Simulated rainfed and fully irrigated productions within each grid cell were multiplied by the associated fractions of harvested areas and added up to calculate the simulated production per grid cell. Historical LU patterns are subject to large uncertainties (Verburg et al., 2011). Alternative maps are for example provided by (Fritz et al., 2015). Here, we use the MIRCA2000 patterns as they make our estimated changes in production consistent to the spatial maps of relative yield changes provided by Rosenzweig et al., 2014. In addition, the total agricultural area derived from MIRCA2000 is consistent with the area of natural vegetation as described by the MAgPIE model and used as reference for the analysis of the biomes model projections of changes in carbon fluxes and stocks (see this section below)."

and

"The present day reference for the total area of natural vegetation is taken from the 1995 MAgPIE pattern. The MAgPIE model is calibrated with respect to the spatial pattern of total cropland to be in line with other data sources, like the MIRCA2000 dataset (Schmitz et al., 2014). That means that the area of natural vegetation assumed here is not in conflict with the total area of harvested land described by MIRCA2000 and used here to calculate crop global production based on the crop model simulations. However, the patterns of individual crops may differ, due to the underlying land use optimization approach."

We have also added three tables listing the basic characteristics of the applied impact models. In addition the Data and Methods section now includes a more detailed description of the processing of the data. Therefore parts of the text from the Result section have been moved up which may also help to make the Result section more readable.

R2.6 The result section is very hard to follow. The authors should describe in more details their results and (either here or in the previous section) how the simulation experiments were conducted. Too be honest I don't like the kind graphics used in Figure 2 and in the supplement. For me it's not intuitive to interpret the overlay of the relative change of two different variables change in production and change in demand).

Answer:
The "Data and Methods" section now includes a more detailed description of how the experiments were designed and how the data are processed. The associated parts have been separated from the discussion of the Results. We hope that this makes the text easier to read.
The comparison of relative changes in Figure 3 (former Figure 2) is definitely a limitation of the study rendering it more an illustration of the kind of required analysis than a quantitative assessment. We now mention this aspect clearly in the Data and Methods section:

"The quantity projected differs from model to model, ranging from yields constrained by current management deficiencies to potential yields under effectively unconstrained nutrient supply (Table 1 and Table S1 of the SI). Therefore, we only compare relative changes in global production to relative changes in demand. Since simulated yield changes may strongly depend on, for example, the assumed level of fertilizer input in the reference period, we consider this aspect as a critical restriction. In this way, the analysis presented here is an illustration of how the proposed decision framework could be filled, rather than a quantitative assessment."

and in the Conclusions

"In addition, not all models are adjusted to reproduce present day observed yields rendering the analysis presented here illustrative rather than a robust quantitative assessment."

R2.7 The description of the socio-economic scenario (SSP2) should be moved from section 3.1 to the previous section and needs to be described in more detail (population growth, growth of demand for agricultural products, GDP development etc.).

Answer:

We have moved the description to the Data and Methods section and explicitly mention population growth and economic development (GDP) as the two variables used to derive the demand.

R2.8 Section 3.2 is not very clearly written. Are all GGCMSs combined with output from all hydrology models? What is the main message?

Answer:
Yes, all each crop model projection is combined with each water model projections. This is clearly mentioned now in the Data and Methods section and explicitly described in the part of the introduction related to the implementation of the decision framework (see Figure 2).

R2.9 One of my main points of criticism is related to the use of the MAGPIE model results (section 3.3). For me it is not clear if the crop pattern within the MIRCA dataset the same as the base year pattern used by MAGPIE. If this is not the case, the calculated land-use changes should not be used for the analysis as the starting conditions are influencing the MAGPIE simulation results which may explain the large differences between the location of some crop types between the respective data sets. It should also be discussed that the MAGPIE cropland pattern depend on the LPJmL crop yields, e.g. in a proper study design LPJmL needs to be replaced by the different crop models to get consistent results. This point needs to be addressed within the discussion.

Answer:
The MAgPIE land use pattern is only used for illustrative purposes as an example of a potential future land use pattern. We could have used any other. We did not invent an arbitrary one because we want to ensure some plausibility as provided by the MAgPIE model with regard to crop-specific production costs, land suitability, and global trade patterns. However, we only consider the pattern plausible but potentially not assuring consistency between food demand and production under different crop model projections.

We fully agree that in proper study design yield projections from each crop model have to be translated into individual land use patterns. In the newly introduced detailed discussion of the practical implementation of the decision framework and Figure 2 this component is made explicit.

We now highlight this point in the Data and Methods section:

"In the context of our study the pattern is only considered a plausible example of a potential future evolution of land use. However, it does not assure consistency between food demand and production for different crop yield projections. To achieve consistency individual crop model projections would have to be translated into individual land use patterns as described in Section 2 and Figure 2."

R2.10 In section 3.3 it should be noted that the 1995 base map is the same as used for the MAGPIE simulations but (I suspect not the same as used for the base cropping pattern). In my opinion this part is only very weakly liked to the rest of the study and can be dismissed. Although there is a reference to the pdf of the risk assessment framework the authors do not explain or even discuss how trade-offs between carbon sequestration and food production should be assessed.

Answer:
We hope that the point is addressed more explicitly in the newly introduced implementation scheme. We also discuss the consistency between the MIRCA2000 crop areas and the area of natural vegetation from MAgPIE in section 3:

"The present day reference for the total area of natural vegetation is taken from the 1995 MAgPIE pattern. The MAgPIE model is calibrated with respect to the spatial pattern of total cropland to be in line with other data sources, like the MIRCA2000 dataset (Schmitz et al., 2014). That means that the area of natural vegetation assumed here is not in conflict with the total area of harvested land described by MIRCA2000 and used here to calculate crop global production based on the crop model simulations. However, the patterns of individual crops may differ, due to the underlying land use optimization approach. Future projections of the total area of natural vegetation are taken from the MAgPIE simulation described above."

R2.11 The discussion should be more detailed: e.g. a comparison to other existing studies needs to be included; the drawbacks and limitations of the current study design should be addressed more clearly (see comments above); application of the risk assessment framework need to be discussed.

Answer:

We have modified the conclusions by setting our study in perspective to other studies, a more detailed description of the application of the decision framework, and an explicit description of the most important limitations. Some of the discussion is also part of the "Results" sections now called "Results and Discussion". The "Conclusions" are modified in the following way:

"The competition between food security for a growing population and the protection of ecosystems and climate poses a dilemma. This dilemma is fundamentally cross-sectoral, and its analysis requires an unprecedented cross-sectoral, multi-impact-model-analysis of the adaptive pressures on global food production and possible response strategies. So far uncertainties in biophysical impact projections have not been included in integrative studies addressing the above dilemma because of a lack of cross-sectorally consistent multi-impact model projections. Here we propose a decision framework that allows for the addition of a multi-impact-model dimension to the available analyses of climate change impacts and response options. The concept allows for an evaluation of different (agricultural) management decisions in terms of the probability of meet a pre-described amount of carbon stored in natural vegetation and bio-energy production under the constraint of a pre-described food demand that have to be fulfilled. The probability is determined by the uncertainty of the biophysical responses to the considered management decision, climate change and increasing levels of atmospheric CO2 concentrations. The proposed framework allows for an evaluation of selected management option but does not include an optimization to find a best solution in view of conflicting interests as provided by usual integrated assessment studies. In this regard it is similar to the integrated framework to assess climate, LU, energy and water strategies (CLEWS) (Howells et al., 2013) while the approach considered here does not include an economic assessment.

To date, a quantification of this probability has been inhibited by the lack of cross-sectorally consistent multi-impact-model projections. Here, simulations generated within ISI-MIP were used to illustrate the first steps to addressing the gap. The spread across different impact models is shown to be a major component of the uncertainty of climate impact projections. In the case of multiple interests and conflicting response measures, this uncertainty represents a dilemma, since ensuring one target with high certainty means putting another one at particularly high risk.

For a full quantification of the probability distributions illustrated in Fig. 1 multiple crop-models simulations have to be translated into a pdf of the “required food production area” given certain demands accounting, for example, for changing trade patterns (Nelson et al., 2013). This translation has already started within the AgMIP-ISI-MIP cooperation and will enable the generation of a probability distribution of the required food production area. However, current estimates (Nelson et al., 2013) are based on crop model runs that do not account for the CO2-fertilization effect and only a limited number of models provide explicit LU patterns in addition to the aggregated area. In addition, not all models are adjusted to reproduce present day observed yields rendering the analysis presented here illustrative rather than a robust quantitative assessment.

To estimate the associated probability of climate protection failure, carbon emissions due to the loss of natural carbon sinks and stocks, particularly including effects of soil degradation, must be quantified. Therefore, the set of demand-fullfilling LU-patterns has to be provided as input for multi-model biomes simulations. ISI-MIP is designed to facilitate this kind of cross-sectoral integration, which can then be employed to fulfill the urgent demand for a comprehensive assessment of the impacts of climate change, and our options to respond to these impacts and socio-economic developments, along with the corresponding trade-offs.

Our illustration of the uncertainty dilemma is by no means complete. In addition to the irrigation scheme considered here, a more comprehensive consideration of management options for increasing crop yields on a given land area is required. To this end, the representation of management within the crop model simulations needs to be harmonized to quantify the effect of different management assumptions on crop-model projections. For example, similar to the rainfed vs full irrigation scenarios, low fertilizer vs high fertilizer input scenarios could be considered allowing for a scaling of the yields according to the assumed fertilizer input. However, not all crop models explicitly account for fertilizer input.

In the longer term initiatives as ISI-MIP will contribute to filling the remaining gaps and finally allow for a probabilistic assessment of cross-sectoral interactions between climate change impacts. For example, the current second round of ISI-MIP will include biomes and water model simulations accounting for LU changes generated based on different crop model projections (see ISI-MIP2 protocol, www.isi-mip.org)."