Anonymous Referee #1

GENERAL COMMENTS

In this manuscript, Yokohata et al. describe a model integration that brings together (mostly) process-based representations of land use decision-making, land surface, hydrology, vegetation, and agriculture. This is part of an important recent trend in making integrated models that actually account for the effects of changing climate and CO2 on agricultural productivity, and how that changing productivity will affect the future trajectory of land use. The manuscript is well-written, with a decent amount of technical detail, as one would hope for a paper in this journal. However, I have reservations about how the integrated model is framed at the beginning of the manuscript. For that reason, coupled with a number of clarifications that need to be made, I suggest that the paper be resubmitted with major revisions.

SPECIFIC COMMENTS

The beginning of the manuscript sets up a loftier goal than is actually achieved by the presented model. I got the impression that the climate system was included as a component, while in reality the demonstrated version uses offline climate forcings. This begins with the model name, which includes MIROC—a well-known climate model. This idea is reinforced in the Abstract at P1 L27–28, in the Introduction at P3 L20–22, and in Sect. 2 at P4 L8–10. In fact, it's unclear why MIROC is included at all—its only relevance to the work presented here is that it's the source of one of the five climate forcings used. It would make more sense to call the integrated model presented here INTEG1, and reserve "MIROC-INTEG1" for a future version that does actually include MIROC coupling.

Thank you very much for your suggestions. The reason why the name of the model is MIROC-INTEG is because the models of terrestrial ecosystem, water management, crop growth and land use are combined with the land surface model (MATSIRO) included in MIROC, and because this integrated model will also be combined with the Earth System Model (MIROC-ES2L, Hajima et al. 2020) in the ongoing work. Various improvements have been made to the MIROC land surface model, MATSIRO (Takata et al. 2003, Nitta et al. 2014, Pokhrel et al. 2012). Unlike standard hydrological models, it is possible for MATSIRO to consistently solve complicated processes related to energy and water balances on land. One of the advantages of running the land surface model alone in MIROC is that it can be used for assessing the impacts of climate change on land, taking into account the uncertainty of future climate projections. HiGWMAT (Pokhrel et al. 2014), MATSIRO combined with a water resources model, has contributed to the Inter-Sector Impact Assessment Project (ISIMIP). On the other hand, since MIROC is the name of a well-known climate model, as the reviewers point out, the model name "MIROC-INTEG" can be misleading to the reader by implying that it involves air-land surface interactions. For this reason, we have re-named the model "MIROC-INTEG-LAND" in the revised manuscript. In addition, it is clearly described that MIROC-

INTEG-LAND couples the land surface model with various sub-models, and it does not include interaction with the atmosphere. Furthermore, important features of the land surface model in MIROC were described earlier in the paper, and the advantages of running only the land surface model in MIROC were described.

The model title has been changed as follows.
MIROC-INTEG-LAND version 1: A global bio-geochemical land surface model with human water management, crop growth, and land-use change

Because of this modification, the model name in the original manuscript (MIROC-INTEG1) is changed to MIROC-INTEG-LAND in the revised manuscript. The abstract was modified as follows.

To investigate these interrelationships, we developed MIROC-INTEG-LAND (MIROC INTEGrated LAND surface model version 1), an integrated model that combines the land surface component of global climate model MIROC (Model for Interdisciplinary Research on Climate) with water resources, crop production, land ecosystem, and land use models.

The introduction was changed as follows.

The model is based on the land surface component of global climate model MIROC (Model for Interdisciplinary Research on Climate version: Watanabe et al., 2010), into which we have incorporated water resources, land-ecosystem, crop growth, and land use models.

The first paragraph of Section 2 is modified to explain that MIROC-INTEG is based on the land surface component of MIROC, MATSIRO. In addition, the advantages of MATSIRO and running the land surface model alone are also explained.

The distinctive feature of MIROC-INTEG-LAND (Figure 1) is that it couples natural ecosystem and human activity models to the land surface component of MIROC, a state-of-the-art global climate model (Watanabe et al., 2010). The MIROC series is a global atmosphere-land-ocean coupled global climate model, one of the models contributing to the Coupled Model Inter-comparison Project (CMIP). MIROC's land surface component, MATSIRO (Minimal Advanced Treatments of Surface Interaction and Runoff, Takata et al. 2003, Nitta et al., 2014) can consider the energy and water budgets consistently on the land grid with a spatial resolution of 1 degree. MIROC-INTEG-LAND performs its calculations over the global land area only, and neither the atmosphere nor ocean components of MIROC are coupled. One of the advantages of running only the land surface model is that it can be used to assess the impacts of land on climate change, taking into account the uncertainties of future atmospheric projections.

In addition to these specific instances of the authors claiming an integration that does not appear to exist, the text of the Introduction sets up MIROC-INTEG1 as being able to "examine the impact of land-use change on the climate system" (P3 L25) and "quantitatively evaluate the interactions and feedback related to climate, water, crop, land use, and ecosystem" (P3 L27). While the work here gets at a proxy variable—terrestrial carbon storage—that relates to the land-atmosphere carbon flux, actually directly assessing land-use impact on climate is impossible without coupling to a climate model. It is also unclear exactly what feedbacks the authors are referring to at P3 L27, considering that most of the sub-models do not seem to be connected in a two-way manner (see Robinson et al., 2018 Fig. 2). Coupling a climate model is clearly outside the scope of the present work, but I want to reiterate that the analyses presented ARE publication-worthy—they just need to be set up in a less misleading way.

Thank you very much for your suggestions. In response to this comment, the two sentences below have been removed in the revised manuscript.

P3 L25 in the original manuscript
By taking into account changes in the socio-economic scenario, it is possible to examine the impact of land-use change on the climate system while simultaneously investigating the impact of climate change on the water and food sector.
P3 L27: MIROC-INTEG1 can quantitatively evaluate the interactions and feedback related to climate, water, crop, land use, and ecosystem. Such an evaluation is simply not possible with conventional integrated assessment and earth system models.

Instead, we added new section 2.2 to state the novelty of MIROC-INTEG-LAND more clearly. We also clearly stated that some of the interaction in MIROC-INTEG-LAND is one-way, but there are some advantages which were not treated in the conventional integrated assessment models (IAMs).

I am also concerned by the relative lack of space spent evaluating TeLMO. Considering that it is the primary piece of model development introduced in this manuscript (as opposed to integration of existing models), the authors should evaluate more than just regional and global cropland area over 12 years (Fig. 7, which by the way needs area units specified). At the very least, similar analyses need to be presented for pasture and forest area.

Thank you very much for your suggestion. We evaluated the regional and global pasture and forest area over 12 years as in Figure 7. This is added in the revised manuscript and explained as follows.

Figure 8 shows a comparison of TeLMO, AIM, and LUH data for pasture. Unlike cropland, pastures are compared with LUH data because there are no long-term global observation data. TeLMO calculates pasture lands such that the area matches that in the AIM for the AIM calculation domain (17 regions around the world). Because AIM treats China and the United States as one region, the results of TeLMO and AIM for China, the United States, and the globe are almost the same. On the other hand, in Australia, TeLMO is closer to LUH. Similarly, Figure 9 shows a comparison between TeLMO, AIM, and FAO data of forest area. TeLMO refers to MODIS data and calculates forest area taking into account deforestation and changes in crop area. Some difference between TeLMO and FAO can be seen, but the two are relatively close. Overall, TeLMO, AIM, and FAO closely agree at the regional scale.

Captions for Figure 8 and 9 are added as follows.

Figure 8: Same as Figure 7, but for the comparison of historical pasture area simulated by MIROC-INTEG (red), AIM/CGE (blue), and LUH (black), using the ratio of cropland area to total area.

Figure 9: Same as Figure 7, but for the historical forest area simulated by MIROC-INTEG (red), AIM/CGE (blue), and FAO (black), using the ratio of cropland area to total area.

According to this modification, the numbering of figures is modified.

I also have a number of other issues I would like the authors to address in a revised version.
- Is livestock feed production included in crop demand?
In this version, livestock feed production is not included in the crop demand. It is explained in the revised manuscript.

In this study, livestock feed demand is not included in $X_{1,k}$.

- Why do protected areas protect only from bioenergy and not food crops or pasture?
In this study, we did not consider the protected area for the calculation of the food cropland and pasture, by assuming that food has a higher priority than ecosystem protection. This point has been explained in the revised manuscript as follows.

In this study, we did not consider the protected area for the calculation of the food cropland and pasture, under the assumption that food has a higher priority than ecosystem protection.

- Sect. A.5 (P19 L15–21): What is "irrigation water stock" and how does it relate to things calculated in HiGWMAT? It seems completely separate, since the controlling parameter Irr_capacity "is estimated at each cell of the grid by MCMC" (P19 L20–21).

A part of the explanation in the original manuscript was not for MIROC-INTEG. The “irrigation water stock” and “*Irr_capacity*” were not calculated in PRYSBI2 of MIROC-INTEG. The soil water calculated in HiGWMAT by considering irrigation (Section 3.1) was passed to PRYSBI2, and then the water stress was calculated in PRYSBI2 by using the soil water. It is explained in the revised manuscript. The below explanation in the original manuscript is removed in the revised version.

The soil water balance in version 2.2 is modeled using a method similar to that described by Neitsch et al., (2005), with two soil layers and no lateral flow. In this method, the water content in each soil layer is updated daily to account for rainfall, snowmelt, sublimation, transpiration, evaporation, and percolation. However, our model does not consider the nitrogen cycle. Moreover, we do not use the irrigation sub-model used in the SWAT model. Instead, we use a simple protocol in which irrigation water is supplied to the top layer of the soil if the crop experiences water stress. Irrigation water is supplied until its stock is exhausted. The size of the irrigation water stock is determined by the parameter Irrcapacity, which is estimated at each cell of the grid by MCMC.

Instead, the method for the calculation of water stress is added in the revised manuscript as follows.

In PRYSBI2, the calculation of water stress follows the SWAT (Neitsch et al., 2005) algorithm. In SWAT, the daily water stress is calculated according to soil water, soil characteristics (field capacity and water content at saturation), root depth and crop field evapotranspiration. PRYSBI2 uses the soil water calculated in HiGW-MAT as explained in Section 3.2. The crop field evapotranspiration is calculated in SWAT according to the leaf area index.

- By using the Kato & Yamagata (2014) biofuel yields map, it seems that changes in biofuel yield are not considered. Could this be added by scaling based on changing yield of wheat and/or maize?

In Kato and Yamagata (2014), the future changes in climate and fertilizer input are considered. It is explained in the revised manuscript as follows.

For biofuel crop yield y_(bio,j), the yield for miscanthus or switchgrass, whichever is greater in a given cell, is calculated for the entire globe by using the biofuel crop model developed in Kato and Yamagata

(2014). The biofuel crop model in Kato and Yamagata (2014) considers the future changes in climate based on the RCP scenarios. In this study, we also consider the future changes in fertilizer input based on the SSPs adopted in Mori et al. (2018). Because of the uncertainty in future fertilizer application for crop management, we set the high end of the N fertilizer input threshold according to Tilman et al. (2011). The nitrogen fertilizer application was set to increase from the current level according to the increasing rate of GDP in the SSP2 scenario up to 160 kg N ha^{-1} yr^{-1} if the fertilizer input at the country level was below 160 kg N ha^{-1} yr^{-1} in the 2000s. Also, the phosphorus fertilizer input in each country was set to follow the same annual increase rate as the nitrogen fertilizer application.

- Historical domestic and industrial water extractions are taken from FAOSTAT; how are projected extractions calculated?

We also use the same data for the future projection. In the revised manuscript, we described this as follows.

While irrigation demand is simulated by the irrigation module, domestic and industrial water uses are prescribed based on the AQUASTAT database of the Food and Agricultural Organization (FAO; see Pokhrel et al., 2012b). We use the same prescribed values for domestic and industrial water uses in both historical and future simulations, as future projections of water withdrawal are not available.

- With regard to adjustment factors for matching LUH2 or AIM land use areas/demand: What is the justification for using a gridcell-level adjustment factor for cropland but region-level adjustment factors for others?

As described in Eq. (B-16), the adjustment factor for pasture is formulated as grid-cell level ($C_{past,j}$, where j denotes index for the 0.5° cell), by using the LUH2 historical data. We use the region-level adjustment factors for managed forest ($C_{manfr,k}$, where k denotes index for the 17 regions defined in AIM) because the grid-level reference data is not available. This is explained in the revised manuscript.

We use the region-level adjustment factors for managed forest ($C_{manfr,k}$) because the grid-level reference data is not available.

- Fig. 2 should be revised to separate (a) input data coming from outside the model system and (b) data being moved between sub-models. Generally, using different kinds of boxes (rounded rectangles vs. circles, for instance) for models vs. data would be helpful. "Atmosphere" should be added to the arrow pointing to Land Ecosystem.

According to the suggestion, Fig. 2 is revised. Input data is outside the model system. We use different kinds of boxes for models and data. We also added arrows pointing from "Atmosphere" to Land ecosystem. Data box cannot be moved between sub-models, but we use a similar format to that used in Robinson et al. 2018, Figs. 3-6, where the data box is placed at the right. The caption of Figure 2 is modified as follows.

Boxes indicate the sub-models and data. For the sub-models, the name and time-step of the models are indicated in the boxes. In the “data” box, the name of the variable saved as a file is 5 indicated. In the “input data” box, information regarding the input data is indicated.

- P3 L2: Misspelling: "temperture"
- Throughout: "Chapters" should be referred to as "sections"
- P6 L25: Unnecessary comma in "et al., (2011)"
- P11 L21: "LUH2h2v"
Thank you very much for the corrections. They are corrected in the revised manuscript.

- P12 L6: What is "mascon"?
We modified the manuscript as follows. We also added new citations (Save et al. 2016, Watkins et al. 2015, Wiese et al. 2016).

For the GRACE data, we use the mean of mass concentration (mascon) products from the Center for Space Research (CSR; Save et al., 2016) at the University of Texas at Austin and the Jet Propulsion Laboratory (JPL; Watkins et al., 2015; Wiese, Yuan, et al., 2016) at the California Institute of Technology.

In the caption of figure 3, it is also described as follows.

The GRACE data shown are the mean of the mass concentration products from two processing centers: CSR and JPL.

- P13 L10: Closing parenthesis should come after "satellite"
- P14 L1: "reproducibility" doesn't seem like the right word. Perhaps "performance"?
- P14 L13: 2a should be 8b
- P14 L20: "global average" should be "global total" or just "total"
Thank you very much again for the corrections. They are corrected in the revised manuscript.

- P16 L15: I'm unclear as to what this explanation means: "Soil carbon is less impacted by the land-use change compared to the above-ground biomass, likely because of the carbon supply from crops in the VISIT calculation."
In the revised manuscript, the reason for "less impacted" is added as follows.

The decrease in soil carbon after deforestation is much smaller than the decrease in above-ground biomass, as the carbon supply from crop residue compensates for the soil carbon loss.

- P16 L20–22: It is unclear how increasing above-ground biomass would negatively affect ecosystem services." In Asia, the decrease in food cropland area tends to increase the above-ground biomass in both the RCP2.6 and RCP8.5 scenarios. Accordingly, even under the mitigation-oriented scenario, considerable changes in ecosystem structure and functions would occur in certain regions, leading to serious deterioration in ecosystem services."
The description in the original manuscript was misleading, and thus we modified the manuscript as follows.

The impact on above-ground biomass is projected to be greater in northwest South America, central Africa, northeast North America, and Australia, where the bioenergy cropland area is expanding. In these regions, even under the mitigation-oriented scenario, considerable declines in ecosystem structure and functions would occur, leading to deterioration, for example, of habitats for natural organisms, water holding capacity, and soil nutrients. Consequently, these functional degradations would degrade ecosystem services such as biodiversity, regulation, and provision. On the other hand, in Asia, the decrease in food cropland area tends to increase the above-ground biomass in both the RCP2.6 and RCP8.5 scenarios, possibly leading to leading to the enhancement of above-ground biomass, and thus ecosystem services.

- P21 L9–10: This is unclear; please revise.
This paragraph describes the differences between TeLMO and the integrated assessment model (IAMs). In general, the IAMs are not grid-based, but divides the world into dozens of regions and describes economic activity in these regions. Therefore, the IAMs 1) calculate the area of agricultural land by using the information of the yield averaged over these regions based on the balance between supply and demand, and 2) allocate the agricultural land by the down-scale method (e.g., Hasegawa et al. 2017). As pointed out by previous works (Alexander et al. 2017), the problem with this method is that it is not possible to explicitly consider spatiotemporal information such as crop yield and production cost when determining land use change in the procedure of 1). TeLMO solves this problem, making it possible to consistently consider the spatiotemporal information such

as crop yields and the balance between supply and demand when allocating the agricultural land, by using the Food Cropland Down-scale Module and the International Trade Module. This is a very important point and was explained in a new section of the text, “2.2 Novelty of MIROC-INTEG-LAND”.

- P28 L6: Citation missing

The citation is added to the revised manuscript (Friedl et al. 2010).

- Fig. 4: Labels (a) and (b) should be referenced in caption.

The caption is modified in the revised manuscript as follows.

Figure 4: Comparison of irrigation demands simulated by MIROC-INTEG-LAND (a) with the results from offline simulations using HiGW-MAT (b) forced by observed climate forcing data (Pokhrel et al., 2015) for 1°×1° grids shown as the mean for 1998- 2002 period.

- Fig. 10: Y-axis units?

It is the cropland in that year as a fraction of total land area. The caption of Figure 12 (Figure 10 in the original manuscript) is modified in the revised manuscript as follows.

Figure 12: Time series of changes in cropland area based on the forcings of the five climate models. The vertical axis is the cropland area as a fraction of total land area.

- Fig. B-1: (1) Bin boundaries should be labeled in terms of real units. (2) What year(s) are being compared? At what resolution? (Include this info in caption, not just main text.)

The information on (1)-(3) is included in the caption of Fig. B-1. The label in Fig. B-1 is also modified. The caption of Figure B-1 is modified as follows.

Figure B-1: Comparison of the global MODIS cropland area and the calculated area using the agricultural suitability index (ASI). Here, 23,000 randomly selected cropland area values are arranged in descending order and divided into 10 categories; the average value of MODIS (black) and ASI values calculated by TeLMO (red) in each category are compared. The horizontal axis is the higher percentile of cropland area data that is randomly selected from the global 0.5 degree grids at year 2005.

In the main text of Appendix B1.1, the sentence is modified as follows.

The logistic regression coefficient was derived from 23,000 data values that were randomly selected from the set of global 0.5° grids at year 2005.

WORKS CITED IN REVIEW

Robinson, D.T., Di Vittorio, A., Alexander, P., Arneth, A., Barton, C.M., Brown, D.G., Kettner, A., Lemmen, C., O'Neill, B.C., Janssen, M., Pugh, T.A.M., Rabin, S.S., Roun- sevell, M., Syvitski, J.P., Ullah, I., Verburg, P.H., 2018. Modelling feedbacks between human and natural processes in the land system. Earth Syst. Dynam. 9, 895–914. doi:10.5194/esd-9-895-2018.