Dear Associate Editor,

We want to thank the Reviewers for their thorough review of our manuscript and their constructive suggestions which helped us improve the quality of this study.

We gladly incorporated these suggestions in the revised manuscript and corrected all minor inconsistencies as pointed out by the Reviewers. It became clear to us from both reviews that more clarity was needed to distinguish the different simulation run scenarios. We therefore changed the naming of the respective parameter set and model version combinations throughout the text and on figures and tables in order to improve the comprehensibility of the study.

Further major changes to the manuscript include the restructuring of several sections, especially the introduction and Section 4.1 and adding more detailed descriptions of the representation of winter cereal (now partly in the Appendix), the new cover cropping and crop rotation routines (Sections 2.2.1 and 2.2.3), and a new figure on latent heat flux over a period of 3 year crop rotation. In addition, some short paragraphs have been added to the discussion and conclusions sections, e.g. on the applicability of the new routines presented in this study for large scale simulations.

Below we give detailed responses to each comment including citations from the revised manuscript.

Again, we thank the Reviewers and the Editor for their time and effort.

Sincerely,

Theresa Boas on behalf of all Co-authors

Replies to comments by Anonymous Referee #1, 8 September 2020

My main critique is that it is difficult to understand the impacts of (1) and (3) in particular. I tried to look into the code, but couldn't quite locate (1) and (3). I suggest the authors to make it clear in the code where these implementations are (perhaps mark it) so that I can follow how much the codes were changed relative to the standard. To gauge theimpacts of (1), I would like to see a winter wheat simulation only at the "DE-RuS" site for with and without (1). You could show how much leaf area index, latent heat and sensible heat of winter wheat changes with this assumption. Similarly, to examine the impact of (3), you could do a simulation of sugar beet and Winter wheat at "DE-RuS" (in this case sugar beet will be rotated, which you already did) and a simulation of Winter wheat only at "DE-RuS". You could also show how much leaf area index, latent heat and sensible heat of winter wheat changes if there was no rotation. Additionally, you can check whether rotation has any impacts on the modeled nitrogen leaching and fixation rates.

Thank you very much for your constructive comments and suggestions. Please find our detailed replies below.

We included a new Figure (Fig. 2) in section 4.1 highlighting the individual effect of the winter wheat subroutines (1) and the modified parameters for winter wheat (2), as well as a combination of both.

(Line 439-449): "The impact of the new winter wheat specific parameterization and the new winter wheat routine, as well as the combination of both is illustrated in Fig. 2. Here we show simulated LAI for the default model and default parameter set (control), the default model with the new parameter set (control + crop specific), the extended winter wheat model with the default parameter set (new routines) and the extended winter wheat model with the new parameter set (new routines + crop specific).

Using only the new crop specific parameter set with the default model configuration resulted in slightly higher LAI values compared to the control run but did not reach the observed maximum LAI values and the growth cycle duration. The implementation of the winter wheat subroutines using the default parameter set led to a more realistic reproduction of the growth cycle duration compared to the control run, but did not yield good correspondence with observed LAI magnitudes. The combination of the new crop specific parameter set and the new winter wheat subroutines resulted in the most realistic LAI dynamics (Fig. 2). "

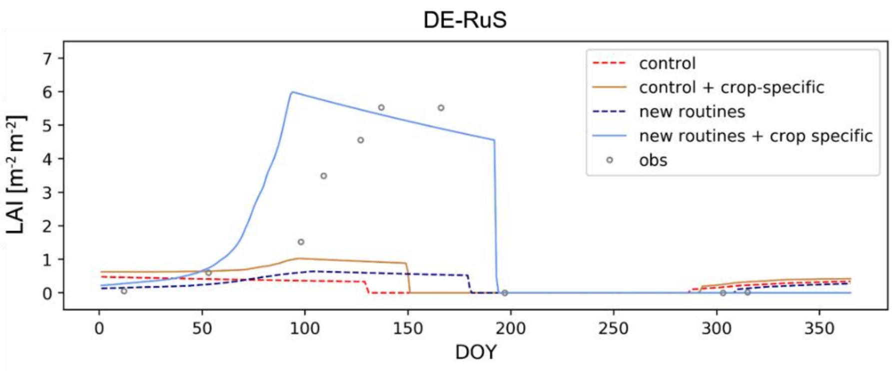

Figure 1: Daily simulation results for the LAI, simulated with default model and the default parameter set (control), the default model with new parameter set (control + crop specific), the extended winter wheat model with default parameterization (new routines) and the extended model with the new parameter set (new routines + crop specific), compared to point observations for a winter wheat year at DE-RuS.

Replies to the list of specific comments by reviewer #1:

(1) While I appreciate some of the details in sections 2.1, and 2.2.1, it would be appropriate it put most of the text in the Appendix section. For example, the paragraph that starts with the description of the default crop phenology scheme (lines 139 to 152 and additional lines) is not new to this study but rather standard CLM5 documentation notes and therefore, they can be put in the Appendix. Similarly, the section about Winter cereal representation that begins with "Vernalization" is also not new to this study. The default phenology scheme of CLM5 has a Vernalization subroutine.

In the revised manuscript, we decided to keep a short description of the winter cereal subroutines and corresponding equations in the main text, for reasons of internal consistency of the paper and for comprehensibility to readers less familiar with specific CLM5 formulations. We added more detail to the description by providing additional equations and explanations to the routine in the Appendix (Eq. A1-A9).

(2) The authors emphasize the importance of cash crops (e.g. sugar beets and potatoes). I would like the authors to comment on the spatial coverage of these crops in Germany and whether the famers are smallholder or largescale holder plantation owners. Along similar lines, it would be good if the authors could comment on how they plan to carry out the large scale simulations or regional simulations for these crops given that you need time series information about the rotation of these crops and also that some crops might be planted every two years or so.

Thanks a lot for the suggestions. We added a paragraph on the local importance of winter wheat, sugar beet and potatoes to the introduction (line 86-92). Also, we added a comment on the applicability of our modifications for large scale simulations in Section 5 (line 717-729).

(Line 86-92): "In Western Europe, a large proportion of arable land is cultivated with rotations of different non-perennial cash crops (Kollas et al., 2015; Eurostat, 2018). The most important cash crops grown in the European Union (EU) are cereals such as wheat (mostly winter wheat varieties in Western Europe), barley and maize, root crops such as sugar beet and potatoes, and oilseed crops such as rape, turnip rape, and sunflower (Eurostat, 2018). Cereals account for the majority of all crop production in the EU, contributing up to 12 % to global cereal grain production (Eurostat, 2018). The EU production of sugar beet accounts for about half of the global production (Eurostat, 2018)."

(Line 717-729): "This new routine can be used to study cover cropping scenarios in future large-scale simulations. The effect of a cover crop during winter months on all crop land units where cash crops are grown in summer could be tested. This could also be tested for specific cash crops only. In addition, it is possible to simulate cover crop plantations based on harvest date thresholds. A defined maximum harvest date for any specific cash crop could define whether a cover crop such as winter wheat would be planted or not. For example, for all sugar beet land units with harvest dates before a certain threshold (e.g. day 290 of any given year) winter wheat could be planted as a cover crop during winter. If this harvest threshold were not reached and the summer crop is harvested late in the year, no cover crop would be planted. Alternatively, these harvest thresholds could define the type of cover crop, e.g. early harvest - winter wheat, late harvest – simple greening mix, etc. Also, historical land use information could be used to simulate realistic cover cropping and crop rotation scenarios. The succession of different crops from historical data could also be used to model the succession of crops for the future. In order to study large scale effects of cover cropping and common crop rotations, the CLM5 model would greatly benefit from further crop specific parameter sets for cover crops such as mustard, and further important cash crops."

(3) A number of statements in the results section is difficult to follow. For example, in lines 407 to 412, there is no reference to any figures. What is green leaf area index in line 408? Do you mean before maturity, during maturity or after maturity?

Thanks for pointing this out. We rephrased and restructured certain parts in this section.

(Line 472-480): "For the BE-Lon site, CLM_WW simulated peak LAI magnitudes are close to the observations. An exception is the year of 2015, where CLM_WW underestimated the unusually high LAI values observed in May and June, which ranged from 5.40 to 6.38 m^2/m^2. For BE-Lon, faster growth was simulated in the early growing stage of winter wheat, resulting in a more gradual increase in LAI compared to the other sites (Figure 3). This is related to higher air temperatures at BE-Lon early in the growing stage (especially in February) that enabled more simulated growth compared to the other sites.

Overall, the LAI peak simulated with CLM_WW occurred about one month earlier than observed, suggesting that maturation was reached too early. This is also reflected in the simulated CLM_WW harvest dates that are approximately one month earlier than the recorded dates (Table 3)."

(4) I think the poor seasonal dynamics and low magnitude of the leaf area index in Figures 2-5 of CLM-D could also be related to the parameter values rather than the winter wheat subroutine that was introduced in this study. There are at least 3 parameter values that are considerably different compared to the default parameters of CLM ('gddmin','hybggg' and 'graincn'). For example, I see that the default gddmin is 50 in the default but 100 in the modified case (this study). Also hybgdd in the modified case is 30 more than the default. So couldn't these likely explain poor seasonal dynamics and low magnitude of the leaf area index in Figures 2-5 of CLM-D?

We believe that we have answered this comment by including Figure 2 and a corresponding discussion in Section 4.1, where we have distinguished the effects of the modified parameter set and the new winter cereal representation, as well as a combination of both.

Please see our first comment above and lines 439-449 in the revised manuscript.

(1) In line 70, Bilinois et al. (2015) is cited but I think the reference is missing.

Thanks a lot for pointing this out. This reference and corresponding paragraph were removed from the revised manuscript in the course of restructuring this section (according to suggestions from RC2).

(2) Please provide fractions of sand, silt and clay in Table 2, maybe up to 5 cm or 10 cm?

We added a table (Table A3) on textural fractions at our study sites to the appendix in the revised manuscript.

(Line 788-790): "Table A1: Textural fractions (sand, silt and clay percentages) for the ICOS and TERENO cropland study sites averaged for the upper soil layers (up to 50 cm) with corresponding reference.

Site/ID	Sand [%]	Silt [%]	Clay [%]	Ref.
Selhausen/DE-RuS	16.4	63.4	14.9	Brogi et al. (2019)
Merzenhausen/DE-RuM	16.4 *	63.4 *	14.9 *	-
Klingenberg/DE-Kli	21.5	22.8	55.7	Grünwald (personal communication, 2020)
Lonzée/BE-Lon	5-10	68-77	18-22	Moureaux et al. (2006)

*adopted from the DE-RuS site"

(3) While I agree with the statement (line 289) that "CLM5 only permits land use changes at the beginning of every year", users can start a CLM5 simulation in any month the land use change actually happens in real life by performing a 'clear-cut' following spin-up, for example.

Yes, re-starting a simulation at any month is possible in order to change CFT. However, this would require a manual restart every time the CFT/PFT changes and does not allow a consecutive simulation with flexible land use changes. While this can be done for point cases, it is not feasible for regional scale cases where CFTs might change at different times and for different land units.

(4) At the "BE-Lon" site, the LAI curve of winter wheat from DOY= 0 to DOY = 100 seems to have a relatively gradual and smooth growth (Figure 2) while at sites "DERuS", "DE-RuM", "DE-Kli", the growth is relatively sudden and steep during the same period. I would like the authors to provide some explanations for this difference.

Thanks for pointing this out. We added a short statement on this.

(Line 474-477): "For BE-Lon, faster growth was simulated in the early growing stage of winter wheat, resulting in a more gradual increase in LAI compared to the other sites (Figure 3). This is related to higher air temperatures at BE-Lon early in the growing stage (especially in February) that enabled more simulated growth compared to the other sites."

(5) In lines 602 to 603, the authors claim that CLM5 does not represent timing of fertilizer. Please provide a citation for this?

Fertilization dynamics and annual fertilizer amounts depend on the crop functional types in CLM5. For all cropping units, mineral fertilizer application starts during the leaf emergence phase of crop growth and continues for 20 days, so there is not much flexibility to represent different fertilization practices (e.g. timing, multiple applications, type of fertilizer etc.).

(Line 142-146): "In CLM5, land fractions with natural vegetation are not influenced by fertilizer application. In cropping units, mineral fertilizer application starts during the leaf emergence phase of crop growth and continues for 20 days. Manure nitrogen is applied at slower rates (0.002 kg N m^{-2} per year by default) to prevent rapid denitrification rates that were observed in earlier CLM versions so that more uptake by the plant is achieved (Lawrence et al., 2018)."

(6) In line 603, the authors state that CLM5 does not consider varieties of winter wheat. I agree with this statement but at the same time, many land surface models don't consider varieties or cultivars of crops. Crops can be genetically modified to boost productivity. This means there could large differences in the parameter estimates among varieties/cultivars. The authors could discuss the variation in the parameter estimates if they are measured at their sites.

Thanks for pointing this out. We added a short discussion on the representation of crop varieties in CLM5 in section 5.

(Line 670-676): "In order to include different varieties of any crop, the list of CTFs could be extended with suitable plant parameterizations. However, this information is not readily available, due to combination of measurement data scarcity and the complexity of the phenology algorithm and parameter scheme. The introduction of a phenology scheme based on plant physiological trait information in CLM could be a major improvement in this field (see Fisher et al., 2019), as plant trait information becomes more readily available (e.g. TRY Plant Trait Database, Kattge et al., 2011). Whether considering different varieties and cultivars of a crop is important for regional or global scale simulations remains to be evaluated."

(7) The authors mention in lines 626 to 629 the following: "There is a tool available for CLM5 that enables the simulation of transient land use and land cover changes (LULCC) (Lawrence et al., 2018). It was designed to simulate and study the effects of changing distributions of natural and crop vegetation, e.g. land use change from forest to agricultural fields (Lawrence et al., 2018), rather than inter-annual changes of agricultural management on crop vegetated areas." I'm confused about the last part "rather than inter-annual changes of agricultural management on crop vegetated areas". Please explain what do you mean by this? Do you mean you cannot change the Nitrogen fertilization rate from year to year in CLM5?

With this we wanted to emphasize that although this tool allows changes in land use every year (on 1st of January), it does not account for changes happening during the year (e.g. several crop growth cycles or changes from summer to winter crop in fall) or multiple crop growth cycles within one year (e.g. multiple growth cycles of the same cash crop within one year in India due to several monsoon seasons). The annual amount of mineral nitrogen fertilization is assigned by plant/crop functional type and can be changed manually for each year.

We rephrased our discussion on this tool accordingly in the revised manuscript.

(Line 701 -709): "There is a tool available for CLM5 that enables the simulation of transient land use and land cover changes (LULCC) (Lawrence et al., 2018). It was designed to simulate the effects of changing distributions of natural and crop vegetation, e.g. land use change from forest to agricultural fields and also allows for changes in crop type between years (Lawrence et al., 2018), but does not account for intra-annual changes of agricultural management on crop vegetated areas that happen in double and triple cropping scenarios. While this tool is useful to study general land use changes by changing the land cover type of individual land units, we found it lacks flexibility in accounting for changes within land units of the same land cover and does not account for all 64 CFTs. Furthermore, this tool changes the CFT of each column on the 1st of January every year according to prescribed values (customized)."

Replies to comments by Anonymous Referee #2, 17 September 2020

Overall: Boas et al. have done considerable work to modify and evaluate simulations of European agriculture in CLM. This work is very exciting and shows significant improvement in model parameterizations and capabilities to add cover crop and crop rotation management practices.
Despite the importance of this work, the text needs to be revised before it is suitable for publication. Some sections require reorganization for clarity, while others will benefit from streamlining to remove redundancies or adding necessary detail. Comments highlighting these sections are included below, as well as specific line comments.

Thank you very much for your constructive feedback and detailed suggestions. Please find our detailed replies to the review comments below.

Abstract.
Line 25: Is cover cropping only common in humid and sub-humid regions? Perhaps it would be more informative to rephrase to something similar to: ".which is an agricultural management technique commonly used in the regions evaluated in this study." Alternatively, you can say that it is a technique growing in popularity to improve soil health and carbon storage.

Thanks, we incorporated your suggestion in the revised manuscript.

(Line 23-26): "The latter modification allows the simulation of cropping during winter months before usual cash crop planting begins in spring, which is an agricultural management technique with a long history that is regaining popularity to reduce erosion and improve soil health and carbon storage and is commonly used in the regions evaluated in this study."

Line 26: Are you referring to the parameterization of new CFTs? Please clarify.

We have clarified this as follows:

(Line 27-31): "We compared simulation results with field data and found that both the new crop specific parameterization, as well as the winter wheat subroutines, led to a significant simulation improvement in terms of energy fluxes (RMSE reduction for latent and sensible heat by up to 57 % and 59 %, respectively), leaf area index (LAI), net ecosystem exchange and crop yield (up to 87 % improvement in winter wheat yield prediction) compared with default model results."

Line 27: Please move the reference of RSME for LH and SH to just after the energy fluxes rather than after NEE.

Thanks, we changed the text accordingly. Please see our response above and line 26-30 in the revised manuscript.

Line 31: When you refer to the "LAI curve", is this the same as the season cycle of LAI? If so, please modify the wording to reflect this.

We rephrased accordingly.

(Line 31-33): "The cover cropping subroutine yielded a substantial improvement in representation of field conditions after harvest of the main cash crop (winter season) in terms of LAI magnitudes and seasonal cycle of LAI, and latent heat flux (reduction of winter time RMSE for latent heat flux by 42 %)."

Lines 31-33: It would be more impactful if you strengthened the last sentence in the abstract. Here is one suggestion: "Our modifications significantly improve model simulations and should therefore be used in future simulations to better understand large-scale impacts of agricultural management on carbon, water, and energy fluxes."

Thanks for your suggestion, we added this accordingly.

(Line 34-36): "Our modifications significantly improved model simulations and should therefore be applied in future studies with CLM5 to improve regional yield predictions and to better understand large-scale impacts of agricultural management on carbon, water and energy fluxes."

Introduction: Overall, the introduction needs some reorganization. You need to more clearly highlight the role of management (make this a separate paragraph, include cover crops but also other types of management). The new representation of cover crops is a primary contribution to this paper and is barely mentioned here. The introduction also needs a broader overview of crops in LSMs (it currently only focuses on AgroIBIS and CLM). Last, most of the introduction emphasizes the global nature of models and that the variation in soils, plants, climate is important. When the reader finally gets to the end of the introduction, which highlights that you focus on a few sites in Europe (which some may argue has narrower variation in soils, plants, climate than if you were to compare to locations from other continents), it makes this study seem limited. It might help to instead describe that models are still limited by their ability to represent many crop types and important management practices, emphasizing the importance of your work adding these new capabilities, and also to highlight that Europe is a major agricultural hub for global food production.

Thank you for your constructive suggestions on the introduction.

Major restructuring was done for this section according to the review comments. Most of the paragraphs were kept and reorganized in the revised manuscript. We added a short overview of crop modules and recent developments in LSMs other than CLM. We commented the regional importance of the simulated cash crops (based on EU statistics) and added more detail to the importance of management practices such as cover cropping and crop rotation. Furthermore, several new references are cited in this section.

Please see Section 1 in the revised manuscript from line 38-110.

Lines 44-49: The mention of cover crops here seems a bit out of place. The earlier part of this paragraph and the start of the next paragraph is focused on adaptation to climate change, whereas the description of cover crops here focuses on soil benefits and climate mitigation. I suggest reorganizing, moving the cover crop description to later in the introduction.

Thanks for your suggestions. We restructured the text accordingly.

(Line 92-100): “The use of cover crops is a common agricultural management practice to reduce soil erosion, soil compaction, and nitrogen leaching as well as to increase agricultural productivity by nitrogen fixation (Sainju et al., 2003; Lobell et al., 2006; Basche et al., 2014; Plaza-Bonilla et al., 2015; Tiemann et al., 2015; Kaye and Quemada, 2017). The biogeochemical effects and benefits of cover crops as well as their potential to mitigate climate change are the focus of many studies (e.g. Sainju et al., 2003; Lobell et al., 2006; Groff, 2015; Plaza-Bonilla et al., 2015; Basche et al., 2016; Carrer et al., 2018; Lombardozzi et al., 2018; Hunter et al., 2019). Despite recent development efforts, the representation of these management practices has not yet been included in CLM5. Furthermore, in a previous study by Lu et al. (2017) the default representation of winter cereals performed poorly in simulating the phenology of winter wheat.”

Lines 68-70: I’m not sure I entirely understand the point of this sentence. Is this just to highlight the evaluation of crops in CLM4.5?

We agree and removed this sentence from the text in the revised manuscript.

Lines 73-76: You should also reference the CLM5 crop overview paper here, which evaluates global crop yields: Lombardozzi, D. L., Y. Lu, P. J. Lawrence, D. M. Lawrence, S. Swenson, K. W. Oleson, W. R. Wieder, and E. A. Ainsworth (2020), Simulating Agriculture in the Community Land Model Version 5, J Geophys Res-Biogeo, 125(8), 927–19, doi:10.1029/2019JG005529.

Thanks for pointing this out, we added Lombardozzi et al. (2020) to our list of references.

Lines 77-84: This paragraph seems too detailed for the introduction. I suggest summarizing and merging with the previous paragraph. For example: “The few studies that have evaluated CLM5 suggest inaccurate phenology and overestimated crop yields (Sheng et al. 2018).” However, you’ll probably want to change/update this to also incorporate results from the Lombardozzi et al. CLM5 paper mentioned above.

Thanks a lot for your suggestions on the introduction. We restructured this section and added the study of Lombardozzi et al. (2020) to the references in the revised manuscript.

Please see section 1 in the revised manuscript from line 38-110.

Methods Overall: The methods section needs to be tidied up. There are redundancies in the first section, and a lack of detail in the cover crop description. Please pay careful attention to providing enough detail that the reader isn’t left wondering how something was done, but keep the text succinct. You reference Lawrence et al. 2018 in several places throughout the text. However, I believe this paper was published in 2019 (not 2018). Please double-check.

Thank you for your constructive suggestions on this section.

We restructured several parts of this section and added Lawrence et al. (2019) to our references. We provided more detail to the winter cereal representation in the appendix, Section 7.1, equations A1-A9.

Additionally, we extended the description of the cover cropping and crop rotation routine in Section 2.2.3.

(Line 303-324): “Individual crop rotation schemes were customized within the code and depend on the currently planted crop type. For example, if a simulation starts with a crop coverage of spring wheat specified in the surface file, the new subroutine is called after harvest of the crop. Within the subroutine, the CFT is then changed to the next crop, e.g. sugar beet. Again, after the harvest of this crop, e.g. sugar beet, the CFT is again changed to the next crop and so on. When the CFT is changed back to spring wheat, the rotation cycle starts again. This rotation is defined in a repetitive sequence based on the harvested CFT and its harvest date:

$$\text{if harvdate}(p) \geq \text{hd}_1 \text{ and ivt}(p) = \text{crop}_1 \text{ then}$$

$$\text{ivt}(p) = \text{crop}_2$$

$$\text{croplive}(p) = \text{false}$$

$$\text{idop}(p) = \text{not\_planted}$$

$$\text{use\_grainproduct} = \text{true}$$

$$\text{else if harvdate}(p) \geq \text{hd}_2 \text{ and ivt}(p) = \text{crop}_2 \text{ then}$$

$$\text{ivt}(p) = \text{crop}_3$$

$$\text{croplive}(p) = \text{false}$$

$$\text{idop}(p) = \text{not\_planted}$$

$$\text{use\_grainproduct} = \text{true} \qquad (7)$$

where harvdate is the harvest day of the current simulation year and hd is the customizable harvest date of the respective CFT, p is the simulated patch on the model grid, ivt is the simulated CFT, $\text{crop}_{1\text{-}3}$ represent the user-specified CFTs to the rotated, idop is the planting day and use_grainproduct is a flag to define whether the grain carbon of simulated crop is to be harvested into the food pool or not. If this flag is set to false, the plant carbon and nitrogen are transferred to the soil litter pool and not allocated to the food product pool upon harvest of the crop.“

Section 2.1:
When describing the crop model, please also cite Lombardozzi et al. (2020), as this has much more detailed information about the crop model updates than Lawrence et al. 2019.
The methods should be streamlined to avoid repetition. For example, allocation is mentioned in lines 134-138, and then again in the paragraph starting at line 153. When referring to C allocation, you state that it varies throughout the growing season (e.g., line 156), whereas the reference to N allocation states that it uses two different C/N ratios (lines 161-162). However, these are treated the same way in the model. Please update for consistency. I suggest switching the order of Eq. 1 and Eq. 2.

Thanks, we revised the text and included a reference to Lombardozzi et al. (2020).

(Line 162-167): “The allocation of carbon and nitrogen also follows the phenology phases. During the leaf emergence phase, carbon from the seed carbon pool is transferred to the leaf carbon pool. Nitrogen is supplied through the soil mineral nitrogen pool. During the grain fill phases, nitrogen from the leaf and stem of the plant is translocated to the grain pool. Allocation ends upon harvest of the crop where grain carbon and nitrogen are transferred from the grain pool to the grain product pool and, a small amount of 3g C m^{-2}, to the seed carbon pool for the next planting (Lawrence et al., 2018; Lombardozzi et al., 2020).”

Line 114: Please define “CFT” the first time you use this term.

Thanks, we corrected this.

Line 115: land units are not separated by fertilizer, only by irrigation. Please update.

We agree that the phrasing is misleading and updates it accordingly:

(Line 128-130): “Vegetated land units are separated into natural vegetation and crop land units, with only one crop functional type (CFT) on each soil column, including irrigation as a CFT specific land management technique (Lawrence et al., 2018; Lombardozzi et al., 2020).”

Lines 204-206: This is a bit confusing and could use clarification. Does the vernalization factor always range from 0-1? Is it applied to GDD for air and soil temperatures (e.g., does it affect all phenological phases)? If it is only applied to grain C allocation, where does the remaining C get allocated?

Yes, the vernalization factor ranges from 0 to 1 (fully vernalized) and affects the GDD in the phenology phase after planting (vernalization starts after leaf emergence and ends before flowering). This leads to a reduced growth when the plant is not fully vernalized and the vf is smaller than 1:

For vf <1

$GDD_o * vf = GDD_n$ with $GDD_n < GDD_o$

where the subscripts $_o$ and $_n$ stand for original and updated GDD.

We added more details to the description of winter cereal representation in the appendix.

(Line 214-216): “The vernalization factor can range between 0 (not vernalized) and 1 (fully vernalized). It is multiplied with the GDD during the phenology phase after planting and the grain carbon allocation coefficient which leads to a reduced growth rate in the beginning of the phenology cycle until the plant is fully vernalized.”

Section 2.2.1
It would be helpful to start with an overview of how winter cereal representation differs from other crops. I suggest a high level overview of why it’s important to include both vernalization and cold tolerance before diving into the details of each.

Thanks for your suggestions. We added a more general paragraph on winter wheat and the two processes – vernalization and cold tolerance.

(Line 182-193): “Winter wheat is an important crop for global food production and covers a significant fraction of the European croplands. (Chakraborty and Newton, 2011; Vermeulen et al., 2012). In general, winter wheat is exposed to a different range of environmental stresses compared to summer crops such low temperatures. In regions with sufficiently cold winters, the main processes that allow a successful cultivation of winter wheat during the colder months are vernalization and cold tolerance (Barlow et al., 2015; Chouard, 1960). Vernalization represents the process that an exposure to a period of non-lethal low temperatures is required to enter the flowering stage for winter crops. In general, the vernalization process ensures that the reproductive development of plants growing over winter (winter crops and also natural vegetation) does not start in late summer or fall but rather in late winter or spring. The other process, cold tolerance, ensures that the crop can acclimate to low temperatures and thus survive cold temperatures and even freeze-thaw cycles. However, cold damage to the crop can occur when the crop is exposed to low temperatures at a certain development stage. These damages have been documented to have significant impacts in crop yield (Lu et al., 2017).”

Equation 4: You specify that Tcrown is slightly higher than the freezing temperature when covered by snow. I see that snow height is used in the calculation, but where is the plant height? Without including the plant height, how do you know whether the plant is covered by snow?

(Line 201-204): “The vernalization process starts after leaf emergence and ends before flowering (Streck et al., 2003) and is dependent on the crown temperature (T_{crown}) (see Eq. A1). The crown is the connecting tissue between the roots and the shoots at the base of the plant. For winter wheat, the crown node is located at about 3 – 5 cm soil depth (Aase and Siddoway, 1979).”

Line 213: The text describes what the accumulative parameters are, but what about the previous time step is used? It would also be useful to include a brief description of how some of the accumulative parameters accumulate (e.g., are these all based on some aspect of accumulated temperature?)

(Line 801-823): “The temperature at which 50 % of the plant is damaged (LT_{50}) is calculated interactively at each time step (LT_{50t}) depending on the previous time step (LT_{50t-1}) and on several accumulative parameters. These parameters are the exposure to near-lethal temperatures ($rate_s$), the stress due to respiration under snow ($rate_r$), the cold hardening or low temperature acclimation (contribution of hardening – $rate_h$) and the loss of hardening due to the exposure to a period of higher temperatures (dehardening – $rate_d$) that are each functions of the crown temperature (Lu et al., 2017 and references therein):

$$\mathrm{LT}_{50\mathrm{t}} = \mathrm{LT}_{50\mathrm{t}-1} - \mathrm{rate}_h + \mathrm{rate}_d + \mathrm{rate}_s + \mathrm{rate}_r \quad \text{(A3)}$$

The exposure to near-lethal temperatures is based on the winter survival model after (Fowler et al., 1999) and is calculated as follows:

$$\mathrm{rate}_s = \frac{\mathrm{LT}_{50\mathrm{t}-1} - T_{\mathrm{crown}}}{e^{-1.9(\mathrm{LT}_{50\mathrm{t}-1} - T_{\mathrm{crown}}) - 3.74}} \quad \text{(A4)}$$

The stress due to respiration under snow is calculated as a function of snow depth (dsnow) that ranges from 0 to 1 for snow cover up to 12.5 cm (equal to 1 for all snow depth higher than 12.5), and a specific respiration factor (RE):

$$\mathrm{rate}_r = R \text{ x } \mathrm{RE} \text{ x } f(\mathrm{dsnow})$$

$$R = 0.54 \; f(\mathrm{dsnow}) = \min(\mathrm{dsnow}, 12.5)/12.5$$

$$\mathrm{RE} = \frac{e^{0.84+0.051\,T_{\mathrm{crown}}-2}}{1.85} \quad \text{(A5)}$$

The contribution of hardening and dehardening are calculated within certain temperature ranges as follows:

For $T_{\mathrm{crown}} < 10°\mathrm{C}$

$$\mathrm{rate}_h = 0.0093(10 - \max(T_{\mathrm{crown}}, 0))(\mathrm{LT}_{50\mathrm{t}-1} - \mathrm{LT}_{50\mathrm{c}}) \quad \text{(A6)}$$

For $T_{\mathrm{crown}} \geq 10°\mathrm{C}$ when vf < 1 (not fully vernalized), and $T_{\mathrm{crown}} \geq -4°\mathrm{C}$ when vf =1 (fully vernalized)

$$\mathrm{rate}_d = 2.7 \times 10^{-5}(\mathrm{LT}_{50\mathrm{i}} - \mathrm{LT}_{50\mathrm{t}-1})(T_{\mathrm{crown}} + 4)^3 \quad \text{(A7)}$$

where LT_{50c} is the maximum frost tolerance of -23 °C and LT_{50i} represents the LT_{50} for an unacclimated plant (LT_{50i} = -0.6+0.142 LT_{50c})."

Equation 6: Please define the "alpha-surv" and the "t" variables in this equation.

Thanks, we corrected this.

(Line 824-828): "The survival rate (f_{surv}) is then calculated as a function of LT_{50} and the crown temperature. The probability of survival is a function of T_{crown} in time (t). It increases once T_{crown} is higher than LT_{50} or decreases when it is lower (Vico et al., 2014):

$$\mathrm{f}_{\mathrm{surv}}(\mathrm{T}_{\mathrm{crown}}, \mathrm{t}) = 2^{-\frac{\mathrm{T}_{\mathrm{crown}}}{\mathrm{LT}_{50}}^{\alpha_{\mathrm{surv}}}} \quad \text{(12)}$$

where α_{surv} is a shape parameter of 4."

Equation 7: I am confused by this, partly because it's not clear what the equation is taking the max of. Also, can Tcrown be negative? That seems to be the only way the solution to this equation isn't 0. Please update to clarify. Also, I think 'fsurf' should in fact be 'fsurv'.

Thanks, we corrected this.

T_{crown} is assumed to be the same as the 2-m air temperature without snow cover and thus can be negative.

(Line 792-800): "The temperature at the crown of the plant (T_{crown}) is assumed to be slightly higher than the 2-m air temperature ($T_{2\mathrm{m}}$) in winter when covered by snow, and the same as the 2-m air temperature without snow cover. Within CLM5, it is calculated separately for temperatures below and above the freezing temperature (T_{frz}):

$$T_{\mathrm{crown}} = 2 + (T_{2m} - T_{\mathrm{frz}}) * (0.4 + 0.0018 * (\min(D_{\mathrm{snow}} * 100, 15) - 15)^2$$

for $T_{2\mathrm{m}} < T_{\mathrm{frz}}$ (A1)

$$T_{\mathrm{crown}} = T_{2m} - T_{\mathrm{frz}}$$

for $T_{2\mathrm{m}} > T_{\mathrm{frz}}$ (A2)

where T_{crown} [K] is the calculated crown temperature, $T_{2\mathrm{m}}$ [K] is the 2-m air temperature, T_{frz} [K] is the freezing point and D_{snow} [m] is the snow height."

Paragraph starting at line 227: I find the description here a little confusing. Can you revise this to more clearly articulate the difference between survival probability and WDD? Is survival probability just a step function, where any value <1 causes the same amount of damage (simulated as part of the C and N pools being transferred to litter)? Should I be thinking of survival probability as the proportion of the plant that survives, or the probability that the whole plant survives? Also, part of my confusion is that this is the first place that a frost damage function is mentioned.

Thanks for your suggestions on this section. We added several more equations and explanations to the appendix. Please see line 789-832 in the revised paper. For a more detailed description we refer to the source literature by Lu et al. (2017) and references therein.

The survival probability is used to calculate the WDD. During the early growing season when the plant is not fully vernalized (vf < 1) and is exposed to subzero temperatures (negative T_{crown}), the survival probability will be low and thus the WDD will be high. It is furthermore used in the subsequent steps to estimate frost damage to the crop. We included two more equations on frost damage in the revised manuscript (Eq. A10 and A11).

(Line 824-856): "The survival rate (f_{surv}) is then calculated as a function of LT_{50} and the crown temperature. The probability of survival is a function of T_{crown} in time (t). It increases once T_{crown} is higher than LT_{50} or decreases when it is lower (Vico et al., 2014):

$$f_{surv}(T_{crown}, t) = 2^{-\frac{T_{crown}}{LT_{50}}^{\alpha_{surv}}} \quad (A8)$$

where α_{surv} is a shape parameter of 4.

The winter killing degree day (WDD) is calculated as a function of crown temperature and survival probability, where the maximum function limits the integration to the potentially damaging periods, when the air temperature (T) is lower than the base temperature (T_{base}) of 0°C (Vico et al., 2014):

$$WDD = \int_{winter} max[(T_{base} - T_{crown}),0]\,[1 - f_{surv}(T_{crown}, t)]dt \quad (A9)$$

Lower LT_{50} indicate a higher frost tolerance and would result in higher survival rates, smaller WDD and less cold damage to the plant. Thus, when the survival probability and crown temperature are low, the WDD will be high (Vico et al., 2014).

Lower LT_{50} indicate a higher frost tolerance and would result in higher survival rates, smaller WDD and less cold damage to the plant. Thus, when the survival probability and crown temperature are low, the WDD will be high (Vico et al., 2014).

The survival probability and the WDD are then used to estimate instant and accumulated frost damage to the crop during the leaf emergence phase (Lu et al., 2017). Instant frost damage is assumed to happen at the beginning of the growing season when the plants are not fully vernalized (vf < 0.9) when the growth of leaves (especially new leaves or small seedlings) due to an exposure to low temperatures. It is simulated by reducing the leaf carbon at low survival probabilities (whenever f_{surv} is below 1). The leaf carbon is reduced by an amount of 5 gC m^{-2} scaled by a factor of 1- f_{surv} that is moved to the carbon litter pool, up to a minimum value of 10 gC m^{-2} leaf carbon:

$$\text{leafc}_t = \text{leafc}_{t-1} - \text{leafc}_{\text{damage}}(1 - f_{\text{surv}})$$

for vf < 0.9, WDD > 0, f_{surv} < 1, and leafc$_t$ > 10 (A10)

where leafc$_t$ is the simulated leaf carbon of the current time step, leafc$_{t-1}$ is the leaf carbon of the previous step and leafc$_{damage}$ is equivalent to 5 gC m^{-2}.

When the plant is close to vernalization towards the end of the leaf emergence phase, it is not as susceptible to suffer from instantaneous frost damage as in the beginning of this phase. Still, an extended period of freezing temperatures can potentially induce damage to the plant (Lu et al., 2017). This accumulated frost damage is simulated based on the accumulated WDD and average survival probability. When the accumulated WDD reaches a value higher than 1° days, the leaf carbon from the previous time step (leafc$_{t-1}$), scaled by the average f_{surv}, is moved to the soil carbon litter pool:

$$\text{leafc}_t = \text{leafc}_{t-1}(1 - \text{average } f_{\text{surv}})$$

for vf ≥ 0.9 and WDD > 1 (A11)

Once this has occurred, the accumulated WDD is reset to 0 and the tracking of the average f_{surv} is restated. Corresponding to the leaf carbon reduction, the leaf nitrogen is reduced from the leaf nitrogen pool to the soil nitrogen litter pool scaled with the parameterized leaf C/N ratio for winter wheat of 20."

Section 2.2.2:
Since you use a pre-existing winter wheat parameterization, it would be helpful to include some information about what you changed in the parameterization and why.

Thanks for pointing this out, we added some more explanations to this part of the text.

(Line 256-263): "In order to yield a reasonable representation of agricultural areas on the regional scale in future studies, the default parameter set was extended with specific crop parameters for sugar beet, potatoes, and winter wheat based on the characteristics of our study sites to better fit the observed plant phenology and energy fluxes at the simulation sites.

The CTFs sugar beet and potatoes are merged to the spring wheat CFT on the default parameter scheme due to the lack of crop specific parameters for these crops. For winter wheat there is a pre-existing default parameter set available in CLM5. However, this default parameterization performed poorly in representing the crop phenology for the evaluated study sites in this study. This was also reported in an earlier study by Lu et al. (2017). Thus, crop specific parameters were added for sugar beet, potatoes and winter wheat."

Table 1: This is a useful summary, but I'm not sure it adds much information to the main text.

We believe that this overview table is helpful information for the reader. Thus, we kept it in the revised manuscript.

Section 2.2.3: How do you determine when the cover crops (or rotations) are planted and the subsequent phenology phases? Is it based on GDD? Did you have to modify GDD parameters or add new ones? Did you add new CFTs to accomplish this? How is allocation determined? This section needs more detail about how modifications were made, as it is the bulk of the development work in this paper.

The rotation schemes are hardcoded in the new cover cropping subroutine. Basically, in the new routine, the phenology algorithm is reset and restarted after harvest of any crop that is assigned with the cover crop flag. We are currently working on a version to make the application more user-friendly, e.g. rotation defined by a control file.

We added more detail to this section in the revised manuscript.

(Line 303-332): "Individual crop rotation schemes were customized within the code and depend on the currently planted crop type. For example, if a simulation starts with a crop coverage of spring wheat specified in the surface file, the new subroutine is called after harvest of the crop. Within the subroutine, the CFT is then changed to the next crop, e.g. sugar beet. Again, after the harvest of this crop, e.g. sugar beet, the CFT is again changed to the next crop and so on. When the CFT is changed back to spring wheat, the rotation cycle starts again. This rotation is defined in a repetitive sequence based on the harvested CFT and its harvest date:

$\text{if harvdate}(p) \geq \text{hd}_1 \text{ and ivt}(p) = \text{crop}_1 \text{ then}$

$\text{ivt}(p) = \text{crop}_2$

$\text{croplive}(p) = \text{false}$

$\text{idop}(p) = \text{not\_planted}$

$\text{use\_grainproduct} = \text{true}$

$\text{else if harvdate}(p) \geq \text{hd}_2 \text{ and ivt}(p) = \text{crop}_2 \text{ then}$

$\text{ivt}(p) = \text{crop}_3$

$\text{croplive}(p) = \text{false}$

$\text{idop}(p) = \text{not\_planted}$

$\text{use\_grainproduct} = \text{true}$ (7)

where harvdate is the harvest day of the current simulation year and hd is the customizable harvest date of the respective CFT, p is the simulated patch on the model grid, ivt is the simulated CFT, $\text{crop}_{1\text{-}3}$ represent the user-specified CFTs to the rotated, idop is the planting day and use_grainproduct is a flag to define whether the grain carbon of simulated crop is to be harvested into the food pool or not. If this flag is set to false, the plant carbon and nitrogen are transferred to the soil litter pool and not allocated to the food product pool upon harvest of the crop.

The actual rotation of crop types can be user-customized by defining the variables hd and crop_x in a list (e.g. hd_1 = 150 [day of year], crop_1= spring wheat, etc.). By including the harvest date as a dependency, it is also possible to simulate the planting of cover crops based on harvest date thresholds. A user-defined maximum harvest date for any specific cash crop can define whether a cover crop would be planted or not. This technique can be beneficial to study the effects of conceptual cover cropping scenarios on regional scales. The possibility to change the CFT within the same year represents a significant improvement in flexibility, as CLM5 only permitted land use changes at the beginning of every year. In order to simulate cover cropping at our study site DE-RuS, we implemented a new CFT for a greening mix cover crop (or covercrop_1)."

Lines 267-270: It's great to hear that you introduced a flag to use the cover crop option, but I'm not sure you need to include that description here.

We believe it is important to inform the reader and potential CLM5 user about the new cover cropping flag.

Lines 276-277: How are you predefining a rotation scheme?

At this stage this is hardcoded in the new subroutine. Please see the revised section 2.2.3 in the manuscript and our response to the comments above.

Line 283: "catch crop" this is the first time you mention it. Are you using this interchangeably with cover crop (which is how you described this in the previous sentence), or are you using a new phrase to distinguish this from cover crop? Please be clear and consistent with word choices.

Here the terms 'cover crop' and 'catch crop' were used synonymously. We corrected this by using only 'cover crop' in the revised manuscript for consistency.

Line 283: You mention plowing the crop into the soil. However, CLM does not represent plowing. How did you accomplish this. Do you assume that the plant biomass is transferred to the litter pool? Also, how did you decide when this happens?

(Line 300-302): "A common practice is to plough the cover crops into the soil instead of removing their biomass from the field. We simulated this by relocating the biomass of the crop into the litter pool instead of the grain product pool upon harvest using the use_grainproduct flag described below (Eq. 7)."

Section 2.3:
I think it would help to describe the sites before the validation data, and/or mention whether you run CLM simulations at these sites. This section starts by describing validation data, but does not mention what is being validated.

We restructured the text accordingly.

(Line 338-339): "The CLM5 model was set up for four European cropland sites: Selhausen, Merzenhausen, Klingenberg and Lonzée (Fig. 1). These sites were selected mainly for their excellent continuous measurements of surface energy fluxes."

Table 2: Useful information about the sites, but I think the map describes the locations quite well, and most of the other information included in the table is not used in the simulation. Therefore, I'm not sure that this table is necessary in the main text.

We think this table gives the reader a nice overview without having to read this section in detail and therefore would like to keep it in the main text. We will include an additional table with textural fractions at the study sites in the appendix of the revised paper as requested by RC1.

Lines 318-319: You mention winter wheat twice here.

Thanks, we correct this.

Lines 341-342: CLM's default time step is 30 minutes.

Here we mean the customized time step of input forcing data, which was set to hourly. Not all meteorological input data was available half-hourly, thus an hourly temporal resolution was used. The internal model time step remains at 30 minutes.

Section 3.1: Throughout this section, the differences in model version versus parameter set seem to be conflated. Please make this much clearer throughout, explaining what each of the model versions includes and what the default versus modified parameter sets include.

Thanks a lot for your suggestion on this section. Changing the wording for our simulation scenarios as well as their description in Section 2.3 as suggested by the reviewer helped us to significantly improve the comprehensibility of our manuscript in this regard.

(Line 403-425): "In order to test the winter wheat representation, several simulations were conducted for all winter wheat years at the sites DE-RuS, DE-RuM, DE-Kli and BE-Lon. In a first step, the impact of each modification was assessed individually by simulating one winter wheat year at the site DE-RuS using four different model configurations: (1) the default model and default parameter set (control), (2) the default model with the new parameter set (control + crop specific), (3) the extended winter wheat model with the default parameter set (new routine), and (4) the extended winter wheat model with the new parameter set (new routine + crop specific). Further evaluations for the other study sites and years were conducted for the combined winter wheat modifications CLM_WW (extended model with winter wheat subroutines and new crop specific parameterization) in comparison to control simulations (default model configuration and default parameterization of winter wheat).

For the evaluation of the crop specific parameter sets for sugar beet and potatoes, simulations were run with the new parameterizations at the sites DE-RuS and BE-Lon over several years. For both sites, control simulations were conducted without the new parameter set, in which both CFTs sugar beet and potatoes are simulated as a spring wheat by default. Furthermore, an evaluation of the default parameterization for the CFT temperate corn at the site DE-Kli is included in the supplementary material (Fig. S1, Table S1).

The cover cropping and crop rotation scheme was tested for two practical cases at DE-RuS. From 2016 to 2017, planting was altered at DE-RuS from barley (here represented by the CFT for spring wheat) in 2016 to sugar beet in 2017 with a greening mix cover crop in between (winter months 2016/2017). In order to simulate this common cover cropping practice, we implemented a new CFT for a greening mix cover crop (or $covercrop_1$). For the years 2017 to 2019 at DE-RuS, the subroutines ability to simulate realistic crop rotation cycles was tested by changing the simulated CFT from sugar beet (2017) to winter wheat (2017-2018) and then to potatoes (2019). In this step, simulations were run with the previously tested crop specific parameterizations for sugar beet, potatoes and winter wheat. Simulation results were again compared to a control simulation run, where a consecutive growth of spring wheat is simulated."

Table 3: Which simulations include the potato and sugar beet parameterization? It looks like it's the CLM_WW simulation, but this needs to be explicitly mentioned in the table description.

We removed the table from the revised manuscript and instead included a more detailed description of the conducted simulation experiments. Please see line 432-457 in the revised manuscript.

Lines 364-366: This text is confusing: It is not clear what the difference is between the default model and the modified model. I assumed the "default" model did not include winter wheat, but this text suggests that it does. How, then, is the default model run with the modified winter wheat parameters different from the winter wheat model with the modified parameters?

The CFT of winter wheat is included in the default model but its specific parameter set yielded very poor representation of simulated winter wheat phenology at our sites and also in previous studies. Thus, next to the implementation of vernalization and cold tolerance representation in the model code, new crop specific parameters were supplied in order to optimize the model performance. Please see our response above to the comment on section 3.1.

Lines 369-370: What are the default parameterizations of sugar been and potatoes?
These aren't included in CLM, so is there a "default"?

Sugar beet and potatoes are included in the structure of the CLM5 crop module and are amongst the 64 CFTs. The CFTs sugar beet and potatoes do not have assigned parameters specifically calibrated for these crops, instead the same parameters as for spring wheat are set as default for these CFTs. We changed the terminology from 'CLM_D' to 'control' throughout the text for better comprehensibility.

(Line 413-415): ". For both sites, control simulations were conducted without the new parameter set, in which both CFTs sugar beet and potatoes are simulated as a spring wheat by default. "

Section 4
In general, I find the use of CLM_D, CLM_WW, and CLM_WW_CC to be confusing, as the changes included in each are not clearly described. Additionally, it seems that sugar beet and potato parameterizations are added to CLM_WW. It might be more helpful to instead refer to CLM_D as "control" or "default" and then refer to updated parameterization (e.g., "improvements to winter wheat" rather than "CLM_WW" in Section 4.1 and "new potato" or "new sugar beet" parameterization in Section 4.2). Additionally, throughout this section, figures should include estimates of uncertainty.

We appreciate your suggestions and incorporated them in the revised manuscript by changing the terminology throughout the text and on figures and tables. Please also see our responses to the reviewer comments on Section 2.3 above.

Due to the small number of compared years (2 to max. 6 years), uncertainty estimates do not add much value to the plots. As briefly discussed in Section 4.1, CLM did not capture inter-annual differences in yield well, showing only minor variations between simulated years. This is also reflected in corresponding simulated LAI curves and energy fluxes that differ only insignificantly from year to year.

(Line 498-501): ". The simulated yields by CLM_WW for the individual years show only minimal variations with values from 8.12 to 8.16 t/ha, while the measured yields ranged from 9.92 to 12.88 t/ha, indicating that CLM did not capture the inter-annual yield variation very well (Table 3)."

Section 4.1: Throughout this section, the text could be streamlined to avoid repeating the description of trends for each site (see note below about Figs. 2-5). Additionally, the trends in energy fluxes are barely mentioned, leaving the reader wondering why you show these in Fig. 2-5, particularly since their mention focuses on cumulated monthly sums (which aren't shown). Also, yields are discussed frequently throughout the text in this section. Is it worth making a bar chart of yields to more clearly illustrate their evaluation? I realize that a bar chart may look

busy, but perhaps averaging across years for the sites with multiple years and including standard deviations will work. Related, how are you calculating yields from CLM simulations? It's important to use the peak daily grain carbon value for the entire growth cycle rather than averaging this over some period of time.
I suggest reorganizing the text (and figures) have 4 paragraphs, focusing on the descriptions of: 1) LAI ; 2) yields; 3) NEE; and 4) energy fluxes. Highlight differences among sites within each paragraph. You can also include an opening paragraph that mentions that CLM_WW improves trends for nearly all variables compared to CLM_D, so the remainder of the discussion focuses on the evaluation of CLM_WW.

Thanks for your suggestions. This section has been extended by a paragraph and new figure (Figure 2) focusing on individual effect of the winter wheat subroutines and the new parameter set for winter wheat. The following text was restructured into four paragraphs, each focusing on certain evaluation variables (LAI, yield, energy fluxes, NEE). The figures (previously Figs. 2 – 6) were merged into a multi-panel figure as suggested by the reviewer (now Fig. 3). Please see also our response to the comment below. Annual performance metrics for the respective simulation runs were added to the supplementary material (Table S2).

Furthermore, a bar plot (Figure 4) showing simulated and observed annual grain yield was added to the manuscript. The simulated crop yield was calculated from the peak value of daily grain carbon.

(Line 502-505): "

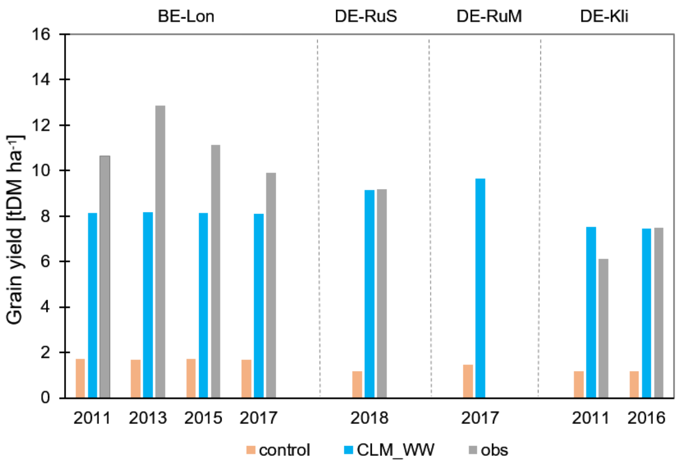

Figure 2: Annual grain yield [tDM/ha] simulated with the control run (orange) and the extended winter wheat model with crop specific parameterization (blue), compared to recorded harvest yields (grey) for all simulated winter wheat years (indicated on the x axis) at the sites BE-Lon, DE-RuS, DE-RuM and DE-Kli."

Figures 2-5: Is it possible to compile these into a single, multi-panel figure? Given that they all show the same variables for different sites, a single panel would allow the reader to compare across sites more easily. Another, possibly better, alternative is to combine all sites and separate the figures into LAI (Fig. 2) and energy fluxes (LH, SH in Fig. 3). It would also allow you to streamline the description of trends throughout Section 4.1. â˘A˘ TIf I understand the legends correctly, simulations and observations in Figs. 2 and 5 are averaged over multiple years. Can you add uncertainty estimates to these plots? If you plot all individual years (it looks like you possibly do that for observations, but not model), it might be easier to plot averages across years and then plot the uncertainty range associated with interannual variability.

Thanks for your suggestion. We rearranged the plots in section 4.1 into one multi-panel figure. Due to the small number of compared years (max. 4 years), uncertainty estimates do not add much value to the plots. As briefly discussed in section 4.1, CLM did not capture inter-annual differences in yield well, showing only minor variations between simulated years. This is also reflected in corresponding simulated LAI curves and energy fluxes that differ only insignificantly from year to year.

(Line 483-490):"

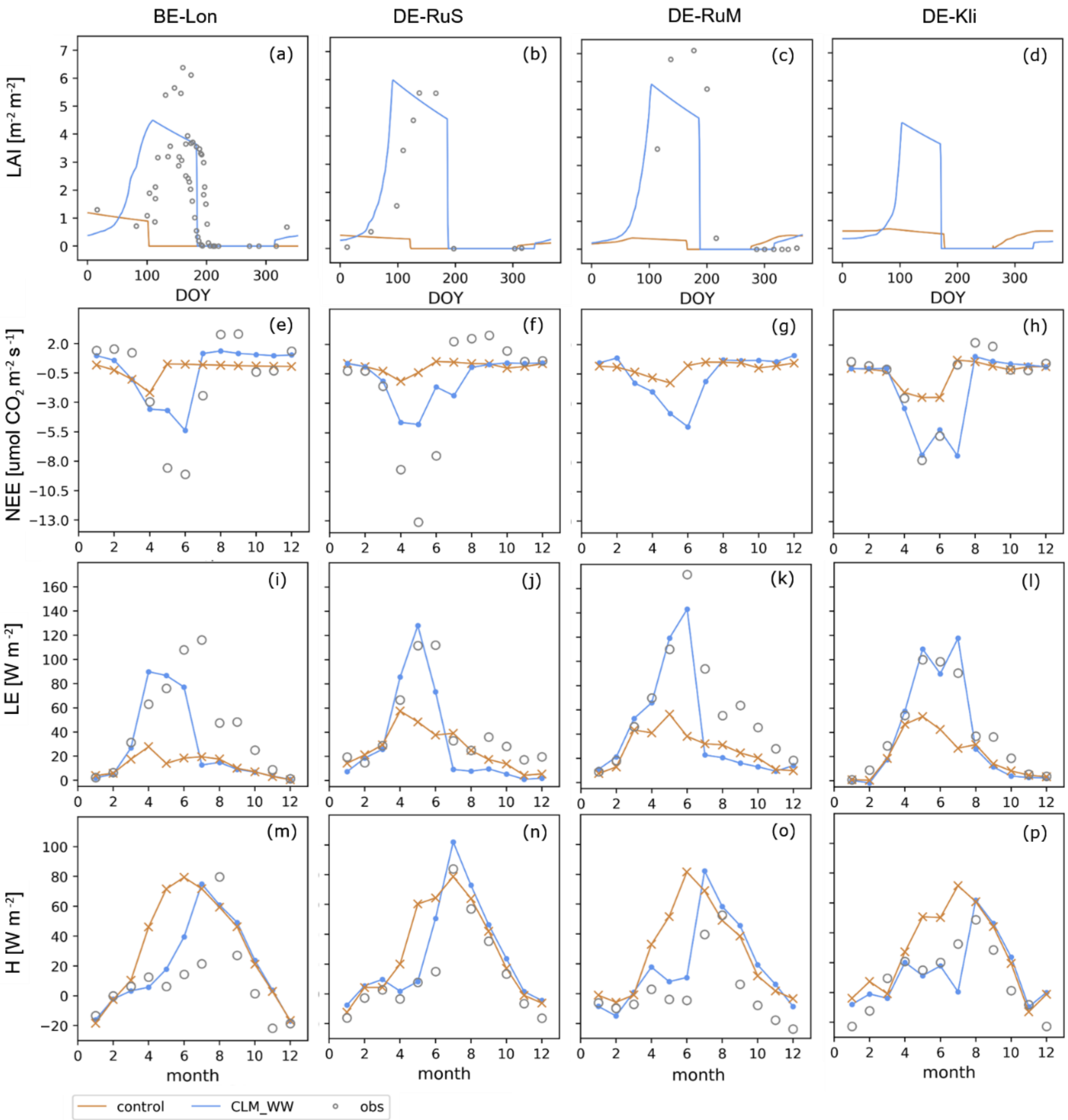

Figure 3: Simulation results of (a-d) LAI and simulation results averaged for each month of (e-h) NEE, (i-l) LE, and (m-p) H for all winter wheat years (see Table 3) at the sites (from left to right) BE-Lon, DE-RuS, DE-RuM and DE-Kli. Simulation results from the new routine with crop specific parameterization – CLM_WW (blue) are compared to control simulations (orange) and available site observations (grey) of LAI (all available point observations plotted) and fluxes (averaged over all respective years and for each month respectively). Corresponding performance statistics for daily simulation results during the crop growth cycle are listed in Table 4."

Fig. 2 states that the observations are GLAI, whereas Figs. 3-5 state that the observations are LAI. Are the observations LAI, GLAI, or does this vary by location? If it is different by location and both LAI and GLAI are used, how might this change the ability to evaluate CLM?

For winter wheat, the green leaf area index (one-sided green leaf area per unit ground surface area) is measured in the field and compared to CLM simulated LAI (defined as one-sided leaf area index, no burying by snow). We used the GLAI synonymously for the LAI for winter wheat and changed the wording in the revised manuscript for consistency.

Fig. 5: There aren't any LAI observations plotted in panel a, yet the figure legend suggests that there should be site observation data for LAI.

Unfortunately, there are no LAI observations available for that year. Please see Figure 3 (above) or line 483-490 of the revised manuscript.

Lines 394-5: As you state, it looks like the LAI peak is indeed too early. However, even more noticeable (and not mentioned) is the fact that the LAI peak looks to be dramatically underestimated.

Thanks, we added this statement.

(Line 452-453): "The default vernalization also resulted in peak LAI occurring too early in the year, leading to significantly lower photosynthesis compared to the observations."

Lines 413-4: Table 4 suggests that crops are only harvested _ 1 month too early, but there are higher observed LH fluxes later in the season than just one month. Is this due to cover cropping, which is not included here?

We have rephrased the text to make this clearer.

(Line 526-530): "The high latent heat fluxes measured at BE-Lon and DE-Kli in the later months of the year (from day 220 onwards) reflect the growth of a cover crop. At both the BE-Lon site as well as at the DE-Kli site, cover crops are typically sown after harvest of winter wheat (mustard at BE-Lon, radish and brassica at DE-Kli), and they strongly affect surface energy fluxes later in the year. In contrast, in the control simulations, as well as in CLM_WW, the crop field were simulated as fallow after the harvest of winter wheat (Fig. 3, Table A1)."

Line 420: I think the phrasing "overestimated early growing season LAI" is potentially misleading. While it is technically correct, the simulated peak LAI values are actually similar to observed peak LAI values, but happen earlier in the year. I think it might be more informative to state that the peak magnitudes are similar, but that the peaks happen too early in the year.

Thanks for pointing this out. We rephrased accordingly.

(Line 470-471): "In general, CLM_WW yielded LAI peak magnitudes similar to observations at the sites BE-Lon, DE-RuS and DE-RuM (Fig. 3)."

(Line 478-479): "Overall, the LAI peak simulated with CLM_WW occurred about one month earlier than observed, suggesting that maturation was reached too early."

Lines 422-3: What does "growing cycle" refer to hear? As you mentioned earlier, LAI peaks too early and planting and harvest start early, suggesting that phenology is not accurate. Therefore, it is unclear what you mean by "generally good correspondence in growing cycle and LAI".

(Line 466-469): "For all study sites and simulation years, CLM_WW simulations resulted in a much better representation of the growth cycle and corresponding seasonal LAI variation and magnitudes compared to control simulations (Fig. 3). Also, the temporal pattern of energy fluxes and NEE were improved with CLM_WW compared to the control run."

Lines 437-8: How can you say that CLM_WW resulted in more realistic magnitudes when you stated in the previous sentence that observations aren't available?

We now compare the LAI results to those for another site and we have rephrased the text accordingly.

(Line 471-472): "For DE-Kli, site-specific observations of the LAI were not available, but simulated LAI magnitudes for DE-Kli using CLM_WW are similar to those for BE-Lon."

Lines 438-9: This is confusing. Does it refer to only the simulations, or also reference the observations? I get the sense that you are conflating simulated peak LAI with simulated and observed crop yields. It implies that lower LAI causes the lower crop yields, although I don't think you can say that for sure.

We have rephrased the text to make this clearer.

(Line 654-660): "Despite the general improvement of winter wheat growth and yield simulated with the modified CLM_WW, there is still potential in further increasing the flexibility towards simulating different crop varieties and management practices. Due to the phenology algorithm of CLM5, a low simulated LAI can indicate a lower grain yield due to low biomass growth. Accordingly, the higher simulated LAI for the DE-RuS site was associated with a slightly higher simulated grain yield for DE-RuS compared to BE-Lon. However, this relationship is not reflected in the observations, as the measured grain yield is lower for DE-RuS compared to BE-Lon, although the observed LAI is higher for DE-RuS (Figure 3, Table 3)."

Line 440: I think this may be backwards. Table 4 suggests that yields are overestimated in 2011 and match really well for 2016.

Thanks, we corrected this.

(Line 494-495): “For DE-Kli, the CLM_WW simulated crop yield matched the recorded yield data very well for the year 2016 and was overestimated for 2011 by approximately 16 %.”

Lines 453-4: Are all the subsequent mentions (including the metrics in Table 5) calculated using the cumulative monthly sums?

The metrics were calculated using simulation output and observation data at daily time step.

(Line 520-523): “However, CLM_WW was able to better capture seasonal variations of surface energy fluxes during the growing cycle of the crop (Fig. 3). The correlation coefficients for the energy fluxes (LE, H and Rn) calculated over the period from planting to harvest date for daily simulation results and daily observation data improved for all sites (Table 4).”

Line 459: You just stated that the BE-Lon sites high some of the highest correlations in the previous sentence, and here single out this site as having high RMSE and biases with low correlations.

Thanks for pointing this out. We corrected this.

(Line 523-534): “Highest correlations were reached for the sites DE-Kli with r values of 0.62 and 0.71 and for BE-Lon with r values of 0.5 and 0.46 for sensible heat and latent heat flux respectively (Table 4). Due to the simulated LAI peak being too early, latent heat flux is underestimated by CLM_WW (Fig. 3, Table 4). The high latent heat fluxes measured at BE-Lon and DE-Kli in the later months of the year (from day 220 onwards) reflect the growth of a cover crop. At both the BE-Lon site as well as at the DE-Kli site, cover crops are typically sown after harvest of winter wheat (mustard at BE-Lon, radish and brassica at DE-Kli), and they strongly affect surface energy fluxes later in the year. In contrast, in the control simulations, as well as in CLM_WW, the crop field were simulated as fallow after the harvest of winter wheat (Fig. 3, Table A1). While the correlation of the latent and sensible heat flux during the growing cycle of the crop is generally increased with the CLM_WW model, the overall annual correlation is still relatively poor due to the influence of cover cropping and poor representation of post-harvest field conditions (annual performance metrics are included in the supplementary material, Table S3).”

Lines 460-461: This sentence should be moved to above, where you briefly mention the mismatch in late-season LH. Also, how does this affect the metrics in Table 5 (see above comments as well).

Thanks for pointing this out. The metrics in Table 5 are calculated for the time between recorded planting and harvest of the crop and thus not affected by this. Please see our response to the comment above, line 523-534 in the revised manuscript, as well as the annual performance metrics included in the supplementary material, Table S3.

Line 464: Are you referring to CLM_WW? I suggest clarifying here, as you do include simulations that represent cover crops.

Up to this point, all simulations were run with either the default model or the model including the new winter cereal representation. The cover cropping approach is then introduced in the next section:

(Line 527-530) “At both the BE-Lon site as well as at the DE-Kli site, cover crops are typically sown after harvest of winter wheat (mustard at BE-Lon, radish and brassica at DE-Kli), and they strongly affect surface energy fluxes later in the year. In contrast, in the control simulations, as well as in CLM_WW, the crop field were simulated as fallow after the harvest of winter wheat (Fig. 3, Table A1).”

Lines 471-2: It is not quite accurate to say that NEE observations match better due to improved LAI. Consider changing to: “in part due to the better representation of LAI”.

Thanks for the suggestion.

(Line 534-535): “Furthermore, CLM_WW was generally better able to match NEE observations compared to control runs, partly due to the better representation of the seasonal LAI variations (Fig. 3).”

Line 473: Are you actually using cumulative monthly values? Fig. 6 show NEE in unites of umol CO2/mˆ2/sˆ1.

We used NEE rates in μmol $CO_2/m^{-2}/s^{-1}$ averaged for the respective month.

Line 475: Both sites? You mentioned three in the previous sentence. If only referring to two sites, please specify which ones.

(Line 539-540): “The resulting correlation for CLM_WW simulations is still relatively low due to an underestimation of the cumulative monthly NEE during seasons with high NEE at BE-Lon and DE-RuS.”

Section 4.2:
Perhaps this should be titled "New Parameterizations" or "Sugar beet and Potato Parameterizations" to distinguish from the modified winter wheat parameterization in Section 4.1 The evaluation of corn here seems a bit out of place since this section focuses primarily on the new parameterizations. I'm not sure where it goes (perhaps in supplemental?), though. Perhaps this section could be refocused as "Evaluation of other crop types", which includes corn and also the new crop types.

We appreciate the suggestions and renamed this section accordingly. The evaluation for temperate corn was moved to the supplement.

(Line 547 onwards): "4.2 Crop specific parameterization of sugar beet and potatoes"

(Line 415-416): "Furthermore, an evaluation of the default parameterization for the CFT temperate corn at the site DE-Kli is included in the supplementary material (Fig. S1, Table S1)."

Lines 489-91: I suggest rephrasing to add some detail: "The modifications to winter wheat in CLM_WW do not affect other crop types. Therefore, we add new parameterizations for sugar beet and potatoes to this code."

Thanks for this suggestion. However, we removed this comment from the revised manuscript because this did not add any crucial information for the reader. Also, this does not have an impact on the study (we could also have used the default model version in this step).

Lines 502-4: Is this parameter set modified, or new? What is it strongly improved compared to, if these didn't exist in CLM? I assume it was compared to the default CLM crop model (where the crop might be represented by another type of crop), and it would help to know for sure.

We changed the wording from 'modified' to 'crop-specific' throughout the text for better comprehensibility.

The CFTs for sugar beet and potatoes exist in the infrastructure of CLM5, yet due to the lack of crop-specific parameterizations, these CFTs (and a number of other CFTs) are merged into the spring wheat CFT within the model code. Thus, although sugar beet and potatoes may be assigned on the simulated land units, the default model basically simulates spring wheat using the corresponding parameterization for spring wheat. In the course of this study, we activated these CFTs within the code to prevent them from being merged into the spring wheat CFT. Consequently, we also supplied crop-specific parameterizations for sugar beet and potatoes.

(Line 548-549): "The crop specific parameter sets were tested for several years with sugar beet and potatoes planting at BE-Lon and DE-RuS respectively."

Line 507: You reference spring wheat here. Is this the crop type that default CLM uses for these sites? If so, you might want to make this clearer (and mention it earlier). For example: "The default parameterization in CLM uses spring wheat for these crop types and effectively reproduced the growth cycle and seasonal LAI, simulations using the potato and sugar beet parameterizations better captured harvest date and growth cycle. "

Thanks for your suggestion.

(Line 549-555): "The performance in reproducing seasonal variations and magnitudes of energy fluxes was strongly improved with the crop specific parameterization. Correspondingly, simulations with the crop specific parameter sets for both sugar beet and potatoes were able to reasonably capture seasonal variations and peak values of LAI as well as growth cycle length and harvest time (Fig. 5, Fig. 6). The control run in CLM uses the spring wheat parameterization for these crop types and therefore reproduced the growth cycle and seasonal LAI of spring wheat, while simulations using the crop-specific potato and sugar beet parameterizations better captured harvest date and growth cycle of these crops."

Line 509: As in previous comments, I don't think "modified" is the best way to describe this. I suggest using "crop-specific parameters" or "parameterizations for new crop types" or similar. As far as I understand, parameters for new crop types were added, not modified.

We appreciate the suggestions and changed the wording accordingly. Please see our responses to the previous comments as well as to Section 3.1.

Lines 510-2: It looks like the latent heat flux is very similar for the other site, which might be worth mentioning.

Thanks for pointing this out. However, as the text is already very extensive we did not want to extend this part of the text any further.

Lines 528-30: Performed better for NEE? Please clarify.

We clarified this:

(Line 591-593): "Simulations of the NEE using the crop specific parameter set yielded a slightly better correlation of 0.58 compared to the control simulation that resulted in a correlation of 0.43 (Table 5)."

Figures 8 & 9: I suggest updating the use of "default" and "modified" here based on above comments. Please specify that the LAI results are daily (if they indeed are).
In previous figures, NEE is described as "cumulative monthly", but here is described as "monthly averaged". Can these be calculated and referred to in the same way for consistency?

We calculated the arithmetic mean of the daily NEE rate for the respective month. The LAI observations are single field measurements (point observations).

(Line 578-582): "Figure 4: Simulation results of (a-b) LAI and monthly averaged simulation results of (c-d) NEE, (e-f) LE, (g-h) H, (i-j) G and (k-l) Rn for all potatoes years (see Table 5) at the sites (left) BE-Lon and (right) DE-RuS. Simulation results for the control run (orange) and the crop specific parameter set (blue) are compared to available site observations (grey) of LAI (all available observations plotted) and fluxes (averaged over all respective years). Corresponding performance statistics for daily simulation results are listed in Table 5."

Section 4.3 It seems that this section focuses on crop rotation as much as cover cropping. I suggest updating the heading to "Cover cropping and crop rotation" or similar to reflect this.

Thanks for the suggestion. We changed the title of this section accordingly.

(Line 601 onwards): "Cover cropping and crop rotation scheme"

Lines 553-4: Is the simulation of a second crop growth onset for the same crop or for the cover crop? The current wording suggests that a second onset is for the same crop within one year AND for the cover crop. If this isn't intended, perhaps change to "simulation of a cover crop as a second crop growth onset within a single year"

The focus is set on the second onset within a single year. Both a second onset of the cash crop, as well as the onset of a cover crop are possible. We rephrased the text for more clarity.

(Line 602-606): "The cover cropping scheme was tested for two fields of application: (1) simulation of a cover crop as a second crop growth onset within a single year, and (2) a more flexible crop rotation between different cash crops. In this step, simulations were run with the previously tested crop specific parameterizations for sugar beet, potatoes and winter wheat and results were again compared to a control simulation run, where a consecutive growth of spring wheat is simulated."

Line 556: "Greening mix" is this the same as cover crop, catch crop? Please be consistent in your terminology throughout.

Thanks for pointing this out, we now use the term 'cover crop' throughout the revised manuscript to be consistent.

(Line 608-609): "A greening mix was planted as a cover crop in between the cash crop rotation of barley (simulated using the spring wheat CFT) in 2016 and sugar beet in 2017."

Lines 556-557: Perhaps it would be more accurate to say "the cash crop rotation of barley (simulated using the spring wheat CFT)".

Thanks for the suggestion. Please see our response above.

Line 557: Spring wheat in CLM is not considered a perennial. It can simulate multiple years of spring wheat in a row, but that doesn't make it perennial.

Thank you for pointing this out.

(Line 609-612): "While only a consecutive growth cycle of spring wheat is simulated in the control run, the new routine was able to represent the crop rotation from barley to sugar beet in the following year as well as a cover crop in between the cash crop cycles."

Lines 559-561: Can the effects of planting cover crops and the crop rotation be isolated?

Here, we wanted to show that not only an easier crop rotation is possible (especially from summer to winter crop) but also the simulation of a crop that is not considered a cash crop. Technically, this follows the same scheme.

Line 563: Please change "plantation" to "planting"

Thanks, we corrected this.

Line 576: Similar to above, spring wheat is not a perennial crop in CLM, as it's planted every growing season.

Thank you for pointing this out. Please see our response to the review comment to line 557 above.

Figures 10-11: It looks like these are for the same site and continuous. Why not plot the full time series on the same panel, adding lines or shading to show the transitions and associated crop type labels. Also, do you not have observational data for LH for 2017-2019 (Fig. 11)?

We appreciate your suggestions. We added a plot of latent heat flux to Figure 8.

(Line 636-641): "

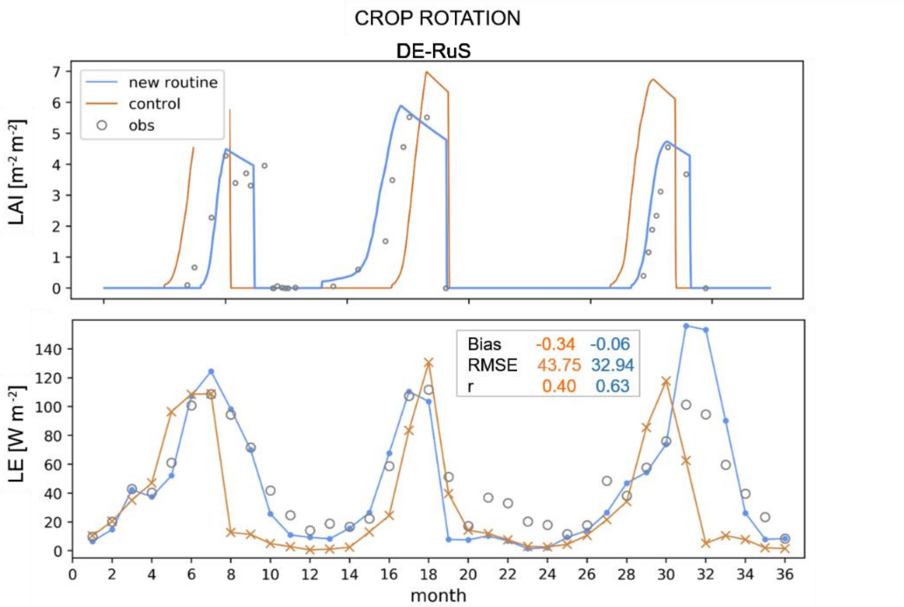

Figure 5: (Top) Simulated LAI for crop rotation from sugar beet (2017) to winter wheat (2017/2018) and to potatoes (2019) at DE-RuS using the new cover cropping subroutine (blue) in comparison to control simulation results with the default phenology algorithm of CLM5 (orange). (Bottom) Corresponding monthly averaged simulation results for the latent heat flux with respective bias, RMSE and r over the whole time interval (calculated using simulation output and observation data at daily time step). Available observation data are plotted in grey."

Section 5

In addition to the benefits and challenges of the new model developments that you include, I was hoping to see further big-picture discussion, for example about how these new developments might improve future large-scale simulations, possible interactions with climate, etc. Consider adding a paragraph to highlight how your improvements can improve our understanding of larger-scale processes. Also, NEE isn't mentioned at all. Why do you think that NEE didn't improve as much as energy fluxes?

Thanks for your suggestions. We added more detail to this part of the discussion.

Field observations indicate that heterotrophic respiration from soil organic matter and litter acts as a carbon source, which is not represented well in CLM5 and is one of the reasons the quality of the NEE simulation is relatively low. Also, a study by Levis et al. (2014) indicated that CLM4.5 underestimated the land use CO_2 by neglecting soil disturbance from cultivation. The authors conclude that the representation of atmospheric CO_2 and soil carbon could be improved in LSMs by accounting for enhanced decomposition from cultivation (Levis et al., 2014).

(Line 650-653): "With an average annual winter wheat yield of around 20 Mt/a for Germany, an improvement of 87 % in simulated yield with CLM_WW compared to the default model (as observed at the DE-Rus site in 2018) could result in a difference of several tens of millions of tons in total predicted annual yield on a nation-wide scale."

(Line 730-740): "In their approach, Lombardozzi et al. (2018) studied the effects of idealized cover crop scenarios by simulating winter crops in all crop regions throughout North America. They found that the effects of cover crops on winter temperatures is strongly related to plant height and LAI and emphasized the importance of biogeophysical effects and varietal selection when evaluating the climate mitigation potential of cover cropping (Lombardozzi et al., 2018). With our new routine, it is now possible to evaluate the biogeophysical effects of cover crops over longer time scales and in combination with typical cash crop rotations throughout agricultural areas. Also the ecological potential of different cover crop varieties could be evaluated. We anticipate that this modification will allow a more realistic representation of seasonal LAI in ecosystems where cover cropping and crop rotations are common management practices. The application of this routine is also of interest for areas with several cash crop cycles within a year like multiple annual crop cycles in India and China (Biradar and Xiao, 2011; Li et al., 2014; Sharma et al., 2015)."

Lines 597-8: As mentioned in a previous comment, higher LAI does not mean higher grain yield. There are many factors that affect yield, including photosynthetic rate, nutrient availability, etc. Also, the results presented in this sentence further support that LAI does not directly correspond to yield: grain yield was higher at BE-Lon (which had lower LAI) than DE-Rus.

Thanks for pointing this out. Please see also our earlier reply to comment line 438-9.

(Line 656-670): "Due to the phenology algorithm of CLM5, a low simulated LAI can indicate a lower grain yield due to low biomass growth. Accordingly, the higher simulated LAI for the DE-RuS site was associated with a slightly higher simulated grain yield for DE-RuS compared to BE-Lon. However, this relationship is not reflected in the observations, as the measured grain yield is lower for DE-RuS compared to BE-Lon, although the observed LAI is higher for DE-RuS (Figure 3, Table 3).

In CLM, there are several variables that influence the simulated crop yield, such as LAI cycle and peak, length of the leaf emergence phase, harvest date, and water availability from the soil. Except for soil moisture, these variables are strongly correlated to the GDD scheme which suggests that the simulated crop yield profoundly depends on the GDD. The high sensitivity of simulated yield in CLM towards GDD is not reflected in actual field observation, where crop yield depends on a multitude of factor, environmental conditions (weather, nutrient availability, atmospheric CO2) and management decisions. Underestimation of winter wheat yield at BE-Lon may be due to model deficiencies in representing the complex crop management practices, such as timing and type of fertilizer, ploughing crop varieties and the usage of different winter wheat varieties that can show different responses to water or heat stress, frost and have different grain productivities (White and Wilson, 2006; Bergkamp et al., 2018; Ceglar et al., 2019)."

Line 603: CLM may not represent different varieties, but the parameters could be changed (as you did here) to represent different varieties, especially when simulated at single points.

Thanks for your suggestions. We added more details:

(Line 670-676): "In order to include different varieties of any crop, the list of CTFs could be extended with suitable plant parameterizations. However, this information is not readily available, due to combination of measurement data scarcity and the complexity of the phenology algorithm and parameter scheme. The introduction of a phenology scheme based on plant physiological trait information in CLM could be a major improvement in this field (see Fisher et al., 2019), as plant trait information becomes more readily available (e.g. TRY Plant Trait Database, Kattge et al., 2011). Whether considering different varieties and cultivars of a crop is important for regional or global scale simulations remains to be evaluated."

Line 607: It might be clearer to say "The early leaf onset and harvest for winter wheat simulated by CLM: : :"

Done as suggested by the reviewer.

Lines 619-22: Can this be more specific? How would discretizing plant hydraulic properties improve yield prediction? Also, why does the reference include "Daniel"? How could the properties (parameters?) be estimated by inverse modeling or data assimilation?

Thanks for pointing this out. We added more details:

(Line 691-699): "Within the crop module of CLM5, the carbon allocation of crops is limited by soil water available to the plant. Thus, both an improved soil hydrology and an improved representation of plant hydraulics could play a major role in improving the quality of yield prediction by the model (Bassu et al., 2014; Kennedy et al., 2019). These plant hydraulic properties could be estimated by inverse modelling or data assimilation (e.g. by assimilating measurement data like NEE, LAI, soil moisture and/or energy fluxes using an augmented state-vector approach). In addition, data assimilation of e.g. in situ or remotely sensed soil moisture data and/or LAI could play a major role in increasing the accuracy of regional yield predictions (e.g. Guérif and Duke, 2000; Launay and Guerif, 2005; de Wit and van Diepen, 2007; Fang et al., 2008; Vazifedoust et al., 2009; Huang et al., 2015; Jin et al., 2018)."

Lines 629-31: Why isn't it applicable to regional simulations? If a simulation is set up to use land use change, the distributions of vegetation, including crop types, will change, even on a point scale, and can be customized by the user if desired.

Thanks for pointing this out. We added more details:

(Line 701-709): "There is a tool available for CLM5 that enables the simulation of transient land use and land cover changes (LULCC) (Lawrence et al., 2018). It was designed to simulate the effects of changing distributions of natural and crop vegetation, e.g. land use change from forest to agricultural fields and also allows for changes in crop type between years (Lawrence et al., 2018), but does not account for intra-annual changes of agricultural management on crop vegetated areas that happen in double and triple cropping scenarios. While this tool is useful to study general land use changes by changing the land cover type of individual land units, we found it lacks flexibility in accounting for changes within land units of the same land cover and does not account for all 64 CFTs. Furthermore, this tool changes the CFT of each column on the 1st of January every year according to prescribed values (customized)."

Line 634: Do you mean before fall of 2018? Fall of 2017 would be the same year.

Thanks, corrected as suggested by reviewer.

Line 635: I don't see Figure 12.

Thanks, we meant Figure 11, now Figure 8.

Section 6

Line 665: Is higher flexibility for crop rotations possible beyond your study and beyond single point simulations? Because it isn't clear how cover cropping was incorporated in the methods, the applicability of this beyond your study or single point sites isn't clear.

Thanks for pointing this out. We added more details:

(Line 717-729): "This new routine can be used to study cover cropping scenarios in future large-scale simulations. The effect of a cover crop during winter months on all crop land units where cash crops are grown in summer could be tested. This could also be tested for specific cash crops only. In addition, it is possible to simulate cover crop plantations based on harvest date thresholds. A defined maximum harvest date for any specific cash crop could define whether a cover crop such as winter wheat would be planted or not. For example, for all sugar beet land units with harvest dates before a certain threshold (e.g. day 290 of any given year) winter wheat could be planted as a cover crop during winter. If this harvest threshold were not reached and the summer crop is harvested late in the year, no cover crop would be planted. Alternatively, these harvest thresholds could define the type of cover crop, e.g. early harvest - winter wheat, late harvest – simple greening mix, etc. Also, historical land use information could be used to simulate realistic cover cropping and crop rotation scenarios. The succession of different crops from historical data could also be used to model the succession of crops for the future. In order to study large scale effects of cover cropping and common crop rotations, the CLM5 model would greatly benefit from further crop specific parameter sets for cover crops such as mustard, and further important cash crops."

Lines 675-8: I appreciate that there are numerous improvements that will improve CLM. However, none of these seem strongly related to the work presented here. For example, there is no evidence that lack of management or incorrect plant hydraulic properties are contributing to model biases.

Thanks for your suggestion, we added a comment that is more specific to our study.

(Line 770-775): "Despite our improvements, there is still a need to further develop certain functionalities and specific routines regarding the crop representation and land management in CLM5 in order to achieve better model performance for agricultural land. The applicability of the routines to large scale simulations would strongly benefit from additional crop specific parameterizations for important cash and cover crops. Also a better representation of ploughing and tillage needs be included in future model versions in order to better account for the effects of cover crops on the terrestrial carbon cycle and their biogeochemical benefits."

Improving the representation of cropland sites in the Community Land Model (CLM) version 5.0

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Abstract. The incorporation of a comprehensive crop module in land surface models offers the possibility to study the effect of agricultural land use and land management changes on the terrestrial water, energy and biogeochemical cycles. It may help to improve the simulation of biogeophysical and biogeochemical processes on regional and global scales in the framework of climate and land use change. In this study, the performance of the crop module of the Community Land Model version 5 (CLM5) was evaluated at point scale with site specific field data focussing on the simulation of seasonal and inter-annual variations in crop growth, planting and harvesting cycles, and crop yields as well as water, energy and carbon fluxes. In order to better represent agricultural sites, the model was modified by (1) implementing the winter wheat subroutines after Lu et al. (2017) in CLM5; (2) implementing plant specific parameters for sugar beet, potatoes and winter wheat, thereby adding the two~~se~~ crop functional types (CFT) for sugar beet and potatoes to the list of actively managed crops in CLM5; (3) introducing a cover cropping subroutine that allows multiple crop types on the same column within one year. The latter modification allows the simulation of cropping during winter months before usual cash crop planting begins in spring, which is an agricultural management technique with a long history that is regaining popularity to reduce erosion and improve soil health and carbon storage and is commonly used in the regions evaluated in this study~~a common agricultural management technique in humid and sub-humid regions~~. We compared simulation results with field data and found that both the new crop specific parameterization~~the parameterization of the CFTs~~, as well as the winter wheat subroutines, led to a significant simulation improvement in terms of energy fluxes (RMSE reduction for latent and sensible heat by up to 57 % and 59 %, respectively), leaf area index (LAI), net ecosystem exchange ~~(RMSE reduction for latent and sensible heat by up to 57 % and 59 % respectively)~~ and crop yield (up to 87 % improvement in winter wheat yield prediction) compared with default model results. The cover cropping subroutine yielded a substantial improvement in representation of field conditions after harvest of the main cash crop (winter season) in terms of LAI ~~curve~~ magnitudes and seasonal cycle of LAI, and latent heat flux (reduction of winter time RMSE for latent heat flux by 42 %). Our modifications significantly improved model simulations and should therefore be applied in future studies with CLM5 to improve regional yield predictions and to better understand large-scale impacts of agricultural management on carbon, water and energy fluxes. ~~We anticipate that our model modifications offer opportunities to improve yield predictions, to study the effects of large-scale cover cropping on energy fluxes, soil carbon and nitrogen pools, and soil water storage in future studies with CLM5.~~

1 Introduction

Crop yield is highly influenced by environmental conditions – weather, nutrient availability, atmospheric CO_2 – and agricultural practices such as irrigation and fertilizer application. Global climate change is widely believed to have an important impact on future agriculture and and consequently food security under changing climate is an important research topic (Lobell et al., 2011; Aaheim et al., 2012; Ma et al., 2012; Gosling, 2013; Rosenzweig et al., 2014). Numerous current crop yield predictions for the 21st century show declining global yield trends and increasing irrigation requirements (Urban et al., 2012; Challinor et al., 2014; Deryng et al., 2014; Rosenzweig et al., 2014; Tai et al., 2014; Levis et al., 2018). General agricultural practices have adapted to changes in climate and inter-annual climate variability by adjusting irrigation amounts and fertilizer application as well as cultivating more resistant varieties of certain crops (Kucharik et al., 2006; Kucharik, 2008). Also, the biogeochemical effects and benefits of cover crops as well as their potential to mitigate climate change are the focus of many studies (Sainju et al., 2003; Lobell et al., 2006; Plaza-Bonilla et al., 2015; Basche et al., 2016; Carrer et al., 2018; Lombardozzi et al., 2018; Hunter et al., 2019). The planting of cover crops is a common agricultural management practice in humid and sub-humid regions to reduce soil erosion, consolidation, and nitrogen leaching and to increase agricultural productivity by nitrogen fixation (Sainju et al., 2003; Lobell et al., 2006; Basche et al., 2014; Plaza-Bonilla et al., 2015; Tiemann et al., 2015; Kaye and Quemada, 2017).

With a trend of declining crop yield and increasing uncertainty in yields in many parts of the world (Urban et al., 2012; Challinor et al., 2014; Deryng et al., 2014; Rosenzweig et al., 2014; Tai et al., 2014; Levis et al., 2018), , understanding the impact of climate change on crop production and improving the its prediction of it at local to global scales is a research topic of great importance to society. Also, agricultural expansion and management practices exert strong influences on physical and biogeochemical properties of terrestrial ecosystems that need to be considered in model simulations of the terrestrial system. HenceThus, the evaluation and advancement improvement of integrated modelling approaches, including through with adequate incorporation of improved crop phenology, the capacity to simulate realistic land management and crop yield in response to climate conditions on regional and global scale are the focus of many studies (Stehfest et al., 2007; Olesen et al., 2011; Van den Hoof et al., 2011; Rosenzweig et al., 2014).

Nevertheless, the sophisticated representation of agricultural land cover in Earth system models (ESMs) remains an ongoing challenge due to the complexity of agricultural management decisions and the variety of different crop types and their respective phenologies. In many land surface models (LSMs) and land components of ESMs, the representation of crops is limited to simplistic schemes lacking the representation of management (e.g. irrigation and fertilization) or to surrogate representation by natural grassland (Betts, 2005; Elliott et al., 2015; McDermid et al., 2017). In recent studies there is a trend towards the The incorporation of a comprehensive crop module in land surface modelsLSMs. These modules offer improved potential offers the possibility to study changes in water and energy cycles and crop production in response to climate, environmental, land use, and land management changes. This m and may help to improve the simulation of biogeophysical and biogeochemical processes on regional and global scales (Kucharik and Brye, 2003; Lobell et al., 2011; Lokupitiya et al., 2009; Levis et al., 2012; Osborne et al., 2015; McDermid et al., 2017; Lawrence et al., 2018; Lombardozzi et al., 2020). For example, the Simple Biophere model (SiB) incorporated a crop module to represent a number of temperate crop varieties which resulted in improved simulated LAI and net ecosystem exchange (NEE) (Lokupitiya et al., 2009). Also, the Joint

UK Land Environment Simulator (JULES) was extended to a global representation of crops which improved simulated LAI and gross primary production (GPP) (Osborne et al., 2015).

Recent versions of CLM (i.e. 4.0, 4.5 and 5.0) have adopted the prognostic crop module from the Agro-Ecosystem Integrated Biosphere Simulator (Agro-IBIS) (Kucharik and Brye, 2003), which has the ability to simulate the soil-vegetation-atmosphere system including crop yields, and has been evaluated in multiple studies (e.g. Twine and Kucharik, 2009; Webler et al., 2012; Xu et al., 2016). Even the simplified version of the Agro-IBIS crop scheme that was implemented in CLM4 led to improved simulation of climate-crop interactions and more comprehensive ecosystem balances than previous CLM versions (Levis et al., 2012). Evaluation studies of CLM4 by Levis et al. (2012) and Chen et al. (2015) revealed significant sensitivities of energy and carbon fluxes to biases in crop phenology, especially for the seasonality of the NEE for managed crop sites where the flux is governed by planting and harvest times. In its latest version, CLM (CLM5) has been extended with an interactive crop module that represents crop management. It includes eight actively managed crop types (temperate soybean, tropical soybean, temperate corn, tropical corn, spring wheat, cotton, rice, and sugarcane), as well as irrigated and non-irrigated unmanaged crops (Lombardozzi et al., 2020). CLM5 is to date the only land surface model that includes time-varying spatial distributions of major crop types and their management (Lombardozzi et al., 2020). Despite these improvements over earlier versions of CLM, the few studies that evaluated CLM5 at point and regional scale suggest inaccurate phenology and crop yield estimates for specific crops (Chen et al., 2018; Sheng et al., 2018). In summary, current crop modules in LSMs are limited by their ability to represent many different crop types and important management practices such as cover cropping, flexible fertilizer application types and amounts, etc. The main challenges are related to the complex parameterization of simulated crop varieties due to their distinct phenology in combination with information scarcity, as well as the complexity of human interaction through management decisions and biogeochemical processes. In addition to irrigation and fertilizer application, crop rotations and cover cropping are important management practices and their consideration is a crucial factor to accurately represent energy fluxes and crop phenology of agricultural sites (or areas) over longer time scales.

In Western Europe, a large proportion of arable land is cultivated with rotations of different non-perennial cash crops (Kollas et al., 2015; Eurostat, 2018). The most important cash crops grown in the European Union (EU) are cereals such as wheat (mostly winter wheat varieties in Western Europe), barley and maize, root crops such as sugar beet and potatoes, and oilseed crops such as rape, turnip rape, and sunflower (Eurostat, 2018). Cereals account for the majority of all crop production in the EU, contributing up to 12 % to global cereal grain production (Eurostat, 2018). The EU production of sugar beet accounts for about half of the global production (Eurostat, 2018). The use of cover crops is a common agricultural management practice to reduce soil erosion, soil compaction, and nitrogen leaching as well as to increase agricultural productivity by nitrogen fixation (Sainju et al., 2003; Lobell et al., 2006; Basche et al., 2014; Plaza-Bonilla et al., 2015; Tiemann et al., 2015; Kaye and Quemada, 2017). The biogeochemical effects and benefits of cover crops as well as their potential to mitigate climate change are the focus of many studies (e.g. Sainju et al., 2003; Lobell et al., 2006; Groff, 2015; Plaza-Bonilla et al., 2015; Basche et al., 2016; Carrer et al., 2018; Lombardozzi et al., 2018; Hunter et al., 2019). Despite recent development efforts, the representation of these management practices has not yet been included in CLM5. Furthermore, in a previous study by Lu et al. (2017) the default representation of winter cereals performed poorly in simulating the phenology of winter wheat.

In this study, we evaluate and enhance the performance of the crop module of CLM5 focusing on the representation of seasonal and inter annual variations in crop growth, planting and harvesting cycles, and crop yields as well as energy and carbon fluxes. First, we have transferred the modified vernalization and cold tolerance routine by Lu et al. (2017) to the CLM5 code to simulate winter cereal in a more meaningful way. Secondly, new crop specific parameter sets for winter wheat, sugar beet and potatoes that were gathered from the literature and from observation data were added to the default parameter scheme. Finally, we extended CLM5 by adding a new crop rotation and cover cropping subroutine that models the growth of winter cover crops and the rotation from a summer to a winter crop within the same year. All modification were tested at point scale at four cropland reference sites of the ICOS (Integrated Carbon Observation System) and TERENO (Terrestrial Environmental Observatory) networks in central Europe.

(Kucharik and Brye, 2003; Lobell et al., 2011; Lawrence et al., 2018).

The recent versions of CLM (i.e. 4.0, 4.5 and 5.0) adopted the prognostic crop module from the Agro-Ecosystem Integrated Biosphere Simulator (Agro-IBIS) (Kucharik and Brye, 2003), which has the ability to simulate the soil-vegetation-atmosphere system including crop yields, and has been evaluated in multiple studies (Twine and Kucharik, 2009; Webler et al., 2012; Xu et al., 2016). Even the simplified version of the Agro-IBIS crop scheme that was implemented in CLM4 led to improved simulation of climate-crop interactions and more comprehensive ecosystem balances than previous CLM versions (Levis et al., 2012). Evaluation studies of CLM4 by Levis et al. (2012) and Chen et al. (2015) revealed significant sensitivities of energy and carbon fluxes to biases in crop phenology, especially for the seasonality of the net ecosystem carbon exchange for managed crop sites where the flux is governed by planting and harvest times. First evaluation studies of the CLM-Crop representation of plant hydraulics and its ability to represent crop growth cycles and ecosystem balance of crop sites are available by Bilionis et al. (2015) for CLM4.5.

In the latest version, CLM (CLM5) has been extended with an interactive crop module that includes fertilizer and irrigation scheme, eight actively managed crop types (temperate soybean, tropical soybean, temperate corn, tropical corn, spring wheat, cotton, rice, and sugarcane), irrigated and unirrigated unmanaged crops. However, so far, only very few studies have evaluated CLM5 with respect to crop simulation performance (e.g. crop yield, growth cycle representation and carbon budgets for agricultural ecosystems) either at single points or at regional and global scales (Chen et al., 2018; Sheng et al., 2018; Danica L. Lombardozzi et al., 2020)(e.g. Chen et al., 2018; Sheng et al., 2018).

Chen et al. (2018) emphasize the importance of model performance evaluations at point scale over long timescales given that plant properties, soil properties and climate vary significantly between sites and the reliable simulation of long-term energy and carbon fluxes and variations in plant phenology remain an important challenge. An assessment of the performance of CLM5 in simulating crop yields at the regional level was conducted by Sheng et al (2018), who used CLM5 to simulate crop yield in northeast China. For maize, they found a general overestimation of LAI and an underestimation of stem and leaf carbon during the growing season, compared to observation data and statistical reports, as well as significant discrepancies in simulated and recorded harvesting and planting dates which resulted in a general overestimation of crop yield (Sheng et al., 2018).

The overall aim of this study is to evaluate and enhance the performance of the crop module of CLM5 focussing on the representation of seasonal and inter-annual variations in crop growth, planting and harvesting cycles, and crop yields as well as energy and carbon fluxes. Simulations were carried out for four cropland reference sites of the ICOS (Integrated Carbon Observation System) and TERENO (Terrestrial Environmental Observatory) networks in central Europe. In order to improve the representation of crop growth as well as energy fluxes on agricultural fields at the point scale, several modifications were made within the code and the parameter configuration of the crop module. Firstly, we transferred and adapted the modified vernalization and cold tolerance routine by Lu et al. (2017) to the CLM5 code and tested it for several single point study sites. Secondly, modified parameter sets for winter wheat, sugar beet and potatoes were gathered from the literature and adopted from observation data and were tested at point scale. Finally, we extended CLM5 by adding a new cover cropping subroutine that models the growth of winter cover crops and the rotation from a summer to a winter crop within the same year.

12 Materials and Methods

1.12.1 Community Land Model

In general, lLand surface models such as CLM5 are broadly applied in scientific studies to simulate water, energy and nutrient fluxes in the terrestrial ecosystem (Niu et al., 2011; Han et al., 2014; Lawrence et al., 2018; Naz et al., 2019). CLM5 represents the latest version of the land component in the Community Earth System Model (CESM) (Lawrence et al., 2018; 2019). Within the modelIn CLM5, simulated land surface fluxes such as latent and sensible heat are driven by atmospheric/meteorological input variables in combination with soil and vegetation states (e.g. soil moisture and LAI) and parameters (e.g. hydraulic conductivity, land cover) (Oleson et al., 2010; Lawrence et al., 2011; Lawrence et al., 2018). The new biogeochemistry and crop module of CLM5 (BGC-Crop) adopted the prognostic crop module from the Agro-Ecosystem Integrated Biosphere Simulator (Agro-IBIS) (Kucharik and Brye, 2003). This incorporation of agriculturally managed land cover may help to improve the general representation of biogeochemical processes on the global scale to better address challenges from land use changes and agriculture practices (e.g. Lobell, Bala, and Duffy, 2006). The CLM5 crop module includes new crop functional types, updated fertilization rates and irrigation triggers, a transient crop management option as well as some adjustments to phenological parameters. Also extensive modifications have been made to the grain C and N pool, e.g. C for annual crop seeding comes from the grain C pool and initial seed C for planting is increased from 1 to 3 gCm^{-2} (D.M. Lawrence et al., 2018, ; P. Lawrence et al., 2019; Danica L. Lombardozzi et al., 2020). Vegetated land units are separated into natural vegetation and crop land units, with only one crop functional type (CFT) on each soil column, including irrigation as a CFT specific land management techniques such as irrigation and fertilization (D.M. Lawrence et al., 2018; Danica L. Lombardozzi et al., 2020). A total of 78 plant and crop functional types are included in CLM5 including an irrigated and unirrigated unmanaged C3 crop, eight actively managed crop types - spring wheat, temperate and tropical corn, temperate and tropical soybean, cotton, rice and sugarcane and 23 crop types without specific crop parameters associated that are merged to the most closely related and parameterised CFTs (Lombardozzi et al., 2020)(Lawrence et al., 2018). For the simulation of those inactive crop types, the specific crop parameters of the spatially closest and most similar out of the eight active crop types are used. Irrigation is simulated dynamically for defined irrigated CFTs in response to soil moisture conditions and is partly based on the implementation of Ozdogan et al. (2010) (Leng et al., 2013; Lawrence et al., 2018). Besides water availability from irrigation and precipitation, crop yield and food productivity greatly depends on fertilization. In CLM5-BGC-Crop, fertilization is represented by adding nitrogen directly to the soil mineral pool (Lawrence et al., 2018). Fertilization dynamics and annual fertilizer amounts depend on the crop functional types and vary spatially and yearly based on the land use and land cover change time series derived from the Land Use Model Intercomparison Project (Lawrence et al., 2019) land use and land cover change time series. In CLM5, land fractions ofwith natural vegetation are not influenced by fertilizer application. In cropping units, mineral fertilizer application starts during the leaf emergence phase of crop growth and continues for 20 days. Manure nitrogen is applied at slower rates (0.002 kg N m^{-2} per year by default) to prevent rapid denitrification rates that were observed in earlier CLM versions so that more uptake by the plant is achieved (Lawrence et al., 2018).

CLM5-BGC-Crop is fully prognostic with regards to carbon and nitrogen in the soil, vegetation and litter at each time step.

The crop phenology as well as the carbon and nitrogen cycling processes follow three phenology phases: phase (1) from planting to leaf emergence, phase (2) from leaf emergence to beginning of grain fill and phase (3) from beginning of grain fill to maturity and harvest. These phenology phases are governed by temperature thresholds and the percentage of Growing Degree Days (GDD) required for maturity of the crop with harvest occurring when maturity is reached (Lombardozzi et al., 2020).~~(Lawrence et al., 2018).~~

The first phenology stage, planting, starts when crop specific 10-day mean temperature thresholds (of both the daily 2-m air temperature T_{10d} and the daily minimum 2-m air temperature $T_{min,10d}$) are met. The transition from planting to leaf emergence (phase 2) begins when the growing degree-days of soil temperature at 0.05 m depth (GDD_{Tsoi}) reaches 1 - 5 % of the GDD required for maturity (GDD_{mat}), depending on a crop specific base temperature for the GDD_{Tsoi}. Grain fill (phase 3) starts with either the simulated 2-m air temperature (GDD_{T2m}) reaching a heat unit threshold (h) of 40 – 65 % of GDD_{mat} or when the maximum leaf area index (L_{max}) is reached. The crop is harvested in one time step when 100 % GDD_{mat} is reached or when the crop specific maximum number of days past planting is exceeded. The LAI is dependent on the specified specific leaf area (SLA) and the calculated leaf C. The SLA as well as the maximum LAI are specified for each crop in the parameter file (Table A2).

~~Allocation of assimilated carbon to the different segments of the plant (leaf, stem, root and reproductive pool) is linked to the phenology phases and ends with the harvesting of the crop. The total amount of assimilated carbon is regulated by availability of soil nitrogen. The allocation of nitrogen is based on the specific C/N ratios in plant tissue that vary throughout the growing season and is therefore also related to crop phenology phases (Lawrence et al., 2018). Allocation of assimilated carbon as well as the allocation to leaf, stem, root and reproductive pools is linked to the crop phenology phases and ends with harvest of the crop. The total amount of assimilated carbon is regulated by availability of soil nitrogen, among other resources. The allocation of nitrogen is based on the specific C/N ratios in plant tissue (varying for roots, stem, leaves, reproductive pools) that vary throughout the growing season and are also related to crop phenology phases (Lawrence et al., 2018). Carbon allocation begins during leaf emergence and is specified using allocation coefficients which represent the fraction of available C that is available to be allocated to each C pool.~~

~~Nitrogen allocation of crops depends on the soil mineral nitrogen concentration and the crop specific C/N ratios for each plant segment – leaves, stems, roots and reproductive organs. The nitrogen allocation scheme uses two different C/N ratios for each crop based on the phenology stages to account for the generally lower C/N ratios early in the growth cycle, higher ratios in later growth stages and the N retranslocation during grain fill.~~

~~For a detailed technical description of the model and all its features, the reader is referred to the technical documentation of CLM5 (Lawrence et al., 2018).~~

The allocation of carbon and nitrogen also follows the phenology phases. During the leaf emergence phase, carbon from the seed carbon pool is transferred to the leaf carbon pool. Nitrogen is supplied through the soil mineral nitrogen pool. During the grain fill phases, nitrogen from the leaf and stem of the plant is translocated to the grain pool. Allocation ends upon harvest of the crop where grain carbon and nitrogen are transferred from the grain pool to the grain product pool and, a small amount of 3g C m^{-2}, to the seed carbon pool for the next planting (~~D.M.~~ Lawrence et al., 2018; ~~Danica L.~~ Lombardozzi et al., 2020).

The total amount of assimilated carbon and nitrogen is regulated by availability of soil nitrogen, among other resources, and also depends on crop specific target C/N ratios in the plant tissue (varying for roots, stem, leaves, reproductive pools) (Lawrence et al., 2018; Lombardozzi et al., 2020).

For a detailed technical description of the model and all its features, the reader is referred to the technical documentation and description of new features in CLM5 (~~D.M.~~ Lawrence et al., 2018,~~;~~ ~~P. Lawrence et al.,~~ 2019; ~~Danica L.~~ Lombardozzi et al., 2020).

~~1.2~~2.2 Model modifications

In the course of this study, three main limitation of CLM5 for the intended simulation of agricultural sites in Western Europe at point scale were identified: (1) the default CLM5-BGC-Crop code and parameterization yielded a very poor representation of crop growth of winter wheat and other winter crops, (2) the default plant parameter data set lacks specific parameterization for several important cash crops (here especially sugar beet and potatoes), and (3) CLM5-BGC-Crop does not allow a second crop growth onset or a second CFT to be grown on the same field within one year. These limitations were met by modifications to the code structure and parameterization of the CLM5-BGC-Crop module described below.

~~1.2.1~~2.2.1 Winter cereal representation

Winter wheat is an important crop for global food production and covers a significant fraction of the European croplands. (Chakraborty and Newton, 2011; Vermeulen et al., 2012). In general, winter wheat is exposed to a different range of environmental stresses compared to summer crops such low temperatures. ~~Vernalization (exposure to a period of non-lethal low temperatures required to enter the flowering stage for winter crops) is a very significant process that distinguishes winter from summer cereal varieties.~~ In regions with sufficiently cold winters, the main processes that allow a ~~It influences the cold tolerance of the crop and allows~~ successful cultivation of winter ~~crops~~ wheat during the colder months are vernalization and cold tolerance (Barlow et al., 2015; Chouard, 1960). Vernalization represents the process that an ~~(~~exposure to a period of non-lethal low temperatures is required to enter the flowering stage for winter crops~~) is a very significant process that distinguishes winter from summer cereal varieties.~~ In general, the vernalization process ensures that the reproductive development of plants growing over winter (winter crops and also natural vegetation) does not start in late summer or fall but rather in late winter or spring. The other process, cold tolerance, ensures that the crop can acclimate to low temperatures and thus survive cold temperatures and even freeze-thaw cycles. However, cold damage to the crop can occur when the crop is exposed to low temperatures at a certain development stage. These damages have been documented to have significant impacts in crop yield (Lu et al., 2017).

Lu et al. (2017) introduced a new vernalization, as well as~~-~~ a cold tolerance and frost damage subroutine~~s~~ in CLM4.5 to better simulate the phenology of winter cereal. ~~LAI and grain yield.~~ For this, they adapted the winter wheat vernalization model from Streck et al. (2003). Streck et al. (2003) evaluated their vernalization algorithm for a wide range of winter wheat cultivars for the purpose of being used in crop model approaches. Furthermore, Lu et al. (2017) implemented a cold tolerance scheme including frost damage representation using the approaches after Bergjord et al. (2008) and Vico et al. (2014). In this study, their modifications were ported to the newer version of the model, CLM5, and tested for several study sites.

Vernalization and cold tolerance are cumulative processes that operate in a certain optimum temperature ranges (that can be different for different crop types and cultivars). The vernalization process starts after leaf emergence and ends before flowering (Streck et al., 2003) and is dependent on the crown temperature (T_{crown}) (see Eq. A1). The crown is the connecting tissue between the roots and the shoots at the base of the plant. For winter wheat, the crown node is located at about 3 – 5 cm soil depth (Aase and Siddoway, 1979). .The daily vernalization dependence is calculated based on the crown temperature (T_{crown}) and the optimum vernalization temperature (T_{opt}), limited to times when the crown temperature lies within the minimum to maximum vernalization temperature (T_{min} and T_{max}) range:

$$vd = \sum \text{fvn}(T_{crown}) = \frac{[2(T_{crown}-T_{min})^{\alpha}(T_{opt}-T_{min})^{\alpha}-(T_{crown}-T_{min})^{2\alpha}]}{(T_{opt}-T_{min})^{2\alpha}} \qquad (21)$$

$$\text{fvn}(T_{crown}) = \frac{2(T_{crown}-T_{min})^{\alpha}(T_{opt}-T_{min})^{\alpha}-(T_{crown}-T_{min})^{2\alpha}}{(T_{opt}-T_{min})^{2\alpha}} \qquad (2)$$

$$\alpha = \frac{ln2}{ln[(T_{max}-T_{min})/(T_{opt}-T_{min})]} \qquad (13)$$

$$vd = \sum \text{fvn}(T_{crown}) = \frac{[2(T_{crown}-T_{min})^{\alpha}(T_{opt}-T_{min})^{\alpha}-(T_{crown}-T_{min})^{2\alpha}]}{(T_{opt}-T_{min})^{2\alpha}} \qquad (2)$$

$$vf = \frac{vd^5}{22.5^5+vd^5} \qquad (43)$$

where vd [-] is the sum of the sequential vernalization dependencedays, fvn [-] is the daily vernalization rate, vf [-] is the vernalization factor, T_{crown} [K] is the crown temperature, T_{opt} [K], T_{max} [K] and T_{min} [K] are the optimum, maximum and minimum vernalization temperatures respectively.

The crown temperature (T_{crown}) is assumed to be slightly higher than the 2-m air temperature (T_{2m}) in winter when covered by snow. It is calculated separately for temperatures below and above the freezing temperature (T_{frz}):

$$T_{crown} = 2 + (T_{2m} - T_{frz}) * (0.4 + 0.0018 * (\min(D_{snow} * 100, 15) - 15)^2$$

for $T_{2m} < T_{frz}$ (4)

$$T_{crown} = T_{2m} - T_{frz}$$

for $T_{2m} > T_{frz}$ (5)

where T_{crown} [K] is the calculated crown temperature, T_{2m} [K] is the 2-m air temperature, T_{frz} [K] is the freezing point and D_{snow} [m] is the snow height.

The vernalization factor is then used in the cold tolerance subroutine to assess the cumulative cold hardening of the plant and its dehardening process when exposed to higher temperatures (see below) and in the adjustment of the GDDs since planting. The GDDs since planting as well as the allocation of C to the grain pool are multiplied by the vernalization factor at each time step. This leads to a reduced growth rate in the beginning of the phenology cycle when the plant is not fully vernalized (vf < 1). The vernalization factor can range between 0 (not vernalized) and 1 (fully vernalized). It is multiplied with the GDD during the phenology phase after planting and the grain carbon allocation coefficient which leads to a reduced growth rate in the beginning of the phenology cycle until the plant is fully vernalized. The vernalization factor is further used in the cold tolerance subroutine to assess the cumulative cold hardening of the plant and the dehardening process when exposed to higher temperatures (see below).

Furthermore, Lu et al. (2017) implemented introduced a scheme to quantify the impacts of frost damage based on the cold tolerance subroutine using the approaches after Bergjord et al. (2008) and Vico et al. (2014). The damage from low temperatures is quantified by three main variables: the temperature at which 50 % of the plant is damaged (LT_{50}), the survival probability (f_{surv}) and winter killing degree days (WDD) (Bergjord et al., 2008; Lu et al., 2017; Vico et al., 2014). A detailed description of these approaches can be found in Bergjord et al. (2008) and Vico et al. (2014).

The temperature at which 50 % of the plant is damaged (LT_{50}) is calculated interactively at each time step ($LT_{50,t}$) depending on the previous time step ($LT_{50,t-1}$) and on several accumulative parameters. These parameters are the exposure to near-lethal temperatures ($rate_s$), the stress due to respiration under snow ($rate_r$), the cold hardening or low temperature acclimation (contribution of hardening – $rate_h$) and ~~,~~ the loss of hardening due to the exposure to a period of higher temperatures (dehardening – $rate_d$) ~~and stress due to respiration under snow ($rate_r$)~~ that are each functions of the crown temperature (Lu et al., 2017 and references therein) (see Eq. A2-A11). ~~.~~

The survival rate (f_{surv}) is then calculated as a function of LT_{50} and the crown temperature. The probability of survival is a function of T_{crown} in time (t). It increases once ~~once~~ T_{crown} ~~the crown temperature~~ is higher than LT_{50} or decreases when it is lower (Vico et al., 2014):

$$f_{surv}(T_{crown}, t) = 2^{-\left(\frac{T_{crown}}{LT_{50}}\right)^{\alpha_{surv}}} \qquad (5)$$

~~$f_{surv}(T_{crown}, t) = 2^{-\left(\frac{T_{crown}}{LT_{50}}\right)^{\alpha_{surv}}} \qquad (6)$~~

where α_{surv} is a shape parameter of 4.

The winter killing degree day (WDD) is calculated as a function of crown temperature and survival probability, where the maximum function limits the integration to the potentially damaging periods, when the air temperature (T) is lower than the base temperature (T_{base}) of 0°C (Vico et al., 2014): ~~. When the survival probability and crown temperature are low, the WDD will be high (Vico et al., 2014).~~

$$WDD = \int_{winter} max[(T_{base} - T_{crown}), 0]\,[1 - f_{surv}(T_{crown}, t)]dt \qquad (6)$$

~~where T_{base} = 0 °C. (7)~~

Lower LT_{50} indicate a higher frost tolerance and would result in higher survival rates, ~~and thus~~ smaller WDD and less cold damage to the plant. Thus, when the survival probability and crown temperature are low, the WDD will be high (Vico et al., 2014).

Lu et al. (2017) also implemented a relationship between frost damage described above and the subsequent growth or carbon allocation of the plant. Whenever the survival factor is less than 1, a small amount of leaf carbon (5 g C m^{-2} per model time step) as well as a small amount of leaf nitrogen (scaled by the prescribed C/N target ratios, Table 1 and Table A2) are transferred to the soil carbon and nitrogen litter pool thus simulating a reduction in growth and/or damage of small/young leaves and seedlings. Additionally, in order to simulate more drastic and instantaneous damage or death of the plant due to a longer duration of lethal temperatures (most likely to occur in spring when the plant has emerged and is close to or already fully vernalized), a second frost damage function is implemented. When WDD > 1° days the frost damage function is triggered, leading to ~~severe~~ crop damage by transferring leaf carbon (amount scaled by the survival probability (1 -f_{surv})) to the soil carbon litter pool.

A more detailed description of these routines can be found in the source literature Lu et al. (2017) and references therein.

~~1.2.2~~2.2.2 ~~Extended~~ Crop specific ~~p~~Parameterization

Table 1: CFT specific phenology and CN allocation parameters.

Parameter	CLM variable name	Units

Phenology		
Minimum planting date for the Northern Hemisphere	min_NH_planting_date	MMDD
Maximum planting date for the Northern Hemisphere	max_NH_planting_date	MMDD
Average 5 day daily temperature needed for planting	planting_temp	K
Average 5 day daily minimum temperature needed for planting	min_planting_temp	K
Minimum growing degree days	gddmin	°days
Maximum number of days to maturity	mxmat	Days
Growing Degree Days for maturity	hygdd	°days
Base Temperature for GDD	baset	°C
Maximum Temperature for GDD	mxtmp	°C
Percentage of GDD for maturity to enter phase 3	lfemerg	% GDDmat
Percentage of GDD for maturity to enter phase 4	grnfill	% GDDmat
Canopy top coefficient	ztopmax	M
Maximum Leaf Area Index	laimx	m^2/m^2
Specific Leaf Area	slatop	m^2/gC
CN ratios and allocation		
Leaf C/:N	leafcn	gC/gN
Minimum leaf C/NC:N	leafcn_min	gC/gN
Maximum leaf C/NC:N	leafcn_max	gC/gN
Fine root C/NC:N	frootcn	gC/gN
Grain C/NC:N	graincn	gC/gN
Fraction of leaf N in Rubisco	flnr	fraction/gNm^{-2}

In order to yield a reasonable representation of agricultural areas on the regional scale in future studies, the default parameter set was extended with specific crop parameters for sugar beet, potatoes, and winter wheat based on the characteristics of our study sites to better fit the observed plant phenology and energy fluxes at the simulation sites. The CTFs sugar beet and potatoes are merged to the spring wheat CFT on the default parameter scheme due to the lack of crop specific parameters for these crops. For winter wheat there is a pre-existing default parameter set available in CLM5. However, this default parameterization performed poorly in representing the crop phenology for the evaluated study sites in this study. This was also reported in an earlier study by Lu et al. (2017). Thus, crop specific parameters were added for sugar beet, potatoes and winter wheat. The parameters to be modified were selected taking into account

In selecting parameters to be modified, the sensitivity analysis and parameter estimation studies by Post et al. (2017) (for version 4.5), Cheng et al. (2020) and Fisher et al. (2019) (for version 5.0) were taken into account. Key parameters as identified by previous studies (Sulis et al., 2015; Post et al., 2017; Lu et al., 2017; Fisher et al., 2019; Cheng et al., 2020) are listed in Table 1. These parameters were added adjusted with values from the literature or site-specific observations to match observed values. General phenology parameters such as the maximum canopy height, planting temperatures, maximum LAI, maximum and minimum planting dates and days for growing were adjusted according to field documentation data and the respective siteincluding planting and harvest dates. A list of plant types, Records on planting and harvest dates as well as crops that were planted for all study sites are listedis provided in Table A1. C/N ratios in leaves and roots for wheat and sugar beet were adapted from Whitmore and Groot (1997), Gan et al. (2011), Sánchez-Sastre et al. (2018) and Zheng et al. (2018). The specific leaf area (slatop) and the fraction of leaf N in Rubisco (flnr) for sugar beet and winter wheat~~and winter wheat~~ were taken from Sulis et al. (2015) and references therein and adopted also for potatoes.

Table A2 provides a~~A~~ full list of default and newly ~~modified~~ added crop specific parameters for the CFTs temperate corn, spring wheat, sugar beet, potatoes and winter wheat~~ can be found in Table A2~~.

~~1.2.3~~2.2.3 Cover cropping and crop rotation scheme

The effect of cover crops on the physical and biogeochemical properties of the land surface alters latent heat flux, albedo and soil carbon and nitrogen storage and can potentially impact local and regional climate (Sainju et al., 2003; Lobell et al., 2006; Möller and Reents, 2009; Plaza-Bonilla et al., 2015; Basche et al., 2016; Carrer et al., 2018; Lombardozzi et al., 2018; Hunter et al., 2019).

In the default BGC phenology, the growth algorithm starts in the beginning of each year, when the crop is not alive on the specific patch. Furthermore, the CLM structure does not allow multiple CFTs to coexist on the same column so that multiple planting phases related to cover cropping over winter months or crop rotations with winter and summer crops, both being very common practices in Europe and worldwide, cannot be accounted for. This might also be an issue when representing ecosystems where agricultural management practices involve multiple sowing and harvest cycles in accordance with the monsoon season (e.g. India). Therefore, a cover cropping subroutine was implemented in the BGC phenology module that affects the onset/offset (crop cycle/fallow) algorithm to allow a second onset period (crop cycle) on the same column.

A cover crop flag was introduced in the parameter file and in the source code. This flag can be set for any CFT in the parameter file and calls the cover-cropping subroutine when it is set to true (covercrop_flag ≠ 0). This allows a flexible handling of this option as well as an application on a larger scale. With this modification, the onset period can start again within one simulation year for another (or the same) CFT. For example, when the maturity of the crop is reached and it has been harvested, the model would by default switch to the next stage (phase 4) where the crop is not alive and the offset (fallow) period begins. The next onset period and GDD accumulation for planting would then start in the subsequent simulation year. In our modified CLM5 version, the cover-cropping subroutine is called before entering into the offset period when the cover-crop flag for the current CFT is set to true. In the cover-cropping subroutine, the CFT is then changed according to a predefined rotation scheme and another onset period and GDD accumulation for planting is initialized.

A common practice is to plough the cover crops into the soil instead of removing their biomass from the field. We simulated this by relocating the biomass of the crop into the litter pool instead of the grain product pool upon harvest using the use_grainproduct flag described below (Eq. 7).

Individual crop rotation schemes were customized within the code and depend on the currently planted crop type. For example, if a simulation starts with a crop coverage of spring wheat specified in the surface file, the new subroutine is called after harvest of the crop. Within the subroutine, the CFT is then changed to the next crop, e.g. sugar beet. Again, after the harvest of this crop, e.g. sugar beet, the CFT is again changed to the next crop and so on. When the CFT is changed back to spring wheat, the rotation cycle starts again. This rotation is defined in a repetitive sequence based on the harvested CFT and its harvest date:

$\text{if harvdate}(p) \geq \text{hd}_1 \text{ and ivt}(p) = \text{crop}_1 \text{ then}$

$\quad \text{ivt}(p) = \text{crop}_2$

$\quad \text{croplive}(p) = \text{false}$

$\quad \text{idop}(p) = \text{not\_planted}$

$\quad \text{use\_grainproduct} = \text{true}$

$\text{else if harvdate}(p) \geq \text{hd}_2 \text{ and ivt}(p) = \text{crop}_2 \text{ then}$

$$\begin{aligned}&\text{ivt}(p) = \text{crop}_3\\&\text{croplive}(p) = \text{false}\\&\text{idop}(p) = \text{not\_planted}\\&\text{use\_grainproduct} = \text{true}\end{aligned}\qquad(7)$$

where harvdate is the harvest day of the current simulation year and hd is the customizable harvest date of the respective CFT, p is the simulated patch on the model grid, ivt is the simulated CFT, $\text{crop}_{1\text{-}3}$ represent the user-specified CFTs to the rotated, idop is the planting day and use_grainproduct is a flag to define whether the grain carbon of simulated crop is to be harvested into the food pool or not. If this flag is set to false, the plant carbon and nitrogen are transferred to the soil litter pool and not allocated to the food product pool upon harvest of the crop.

The actual rotation of crop types can be user-customized by defining the variables hd and crop_x in a list (e.g. hd_1 = 150 [day of year], crop_1= spring wheat, etc.). By including the harvest date as a dependency, it is also possible to simulate the planting of cover crops based on harvest date thresholds. A user-defined maximum harvest date for any specific cash crop can define whether a cover crop would be planted or not. This technique can be beneficial to study the effects of conceptual cover cropping scenarios on regional scales. The possibility to change the CFT within the same year represents a significant improvement in flexibility, as CLM5 only permitted land use changes at the beginning of every year.

~~First, the new subroutine was tested for a hypothetical rotation of two cash crops (spring wheat and sugar beet), allowing a green stubble to evolve over winter rather than simulating bare soil. Secondly, two realistic scenarios were tested for DE-RuS. From 2016 to 2017, planting was altered at DE-RuS from barley (here represented by the CFT for spring wheat) in 2016 to sugar beet in 2017 with a greening mix cover crop coverage (winter months 2016/2017) in between. The catch crop was ploughed into the soil prior to the planting of sugar beet in 2017.~~ In order to simulate ~~this common~~ cover cropping at our study site~~practice~~ DE-RuS, we implemented a new CFT for a greening mix cover crop (or ~~catch~~ covercrop~~-1~~). ~~For this CFT, the CN allocation algorithm was changed in such way that, when the plant reaches maturity, the plant carbon and nitrogen are transferred to the soil litter pool and not allocated to the food product pool.~~

~~For the years 2017 to 2019 at DE-RuS, the subroutines ability to simulate realistic crop rotation cycles was tested by changing the simulated CFT from sugar beet (2017) to winter wheat (2017-2018) and then to potatoes (2019). This possibility to change the CFT within the same year represents a significant improvement of CLM, since CLM5 only permits land use changes at the beginning of every year.~~

~~1.3~~2.3 Study sites and validation data

Table 2: ICOS and TERENO cropland study site location coordinates and altitude (Alt.), soil types, Köppen-Geiger climate classification (Peel et al., 2007), mean annual temperature (T), mean annual precipitation amounts (P) and reference. Textural fractions for the top soil layers (up to 50 cm) at each study site are provided in Table A3.

Site/ID	Project	Location	Alt. [msl]	Soil type	Climate	T [°C]*	P [mm/a]*	Ref.
Selhausen DE-RuS	TERENO ICOS	50.865°N 6.447°E	104.5	Luvisol	Cfb - temperate maritime	9.9	698	Ney et al. (2017)
Merzenhausen DE-RuM	TERENO	50.930°N 6.297°E	100	Cambisol	Cfb - temperate maritime	9.9	698	Bogena et al. (2018)
Klingenberg DE-Kli	ICOS	50.893°N 13.522°E	478	Gleysoil	Cfb – suboceanic, subcontinental	8.1	766	Grünwald (personal communication, 2020)
Lonzée BE-Lon	ICOS	50.553°N 4.746°E	167	Luvisol	Cfb - temperate maritime	10	800	Buysse et al.(2017)

* Reference periods: 1961-2010 for DE-RuS (adapted also for DE-RuM), 2005-2019 for DE-Kli and 2004-2017 for BE-Lon.

~~Site specific measurement records of latent and sensible heat fluxes, net ecosystem exchange (NEE), LAI, soil temperature and soil moisture were used as validation data. The sites (Selhausen, Merzenhausen, Klingenberg and Lonzée) were selected mainly for their excellent meteorological records and validation data.~~

The CLM5 model was set up for four European cropland sites: Selhausen, Merzenhausen, Klingenberg and Lonzée (Fig. 1). These sites were selected mainly for their excellent continuous measurements of surface energy fluxes.

Selhausen (50.86589°N, 6.44712°E) is part of the TERENO Rur Hydrological Observatory (Bogena at al., 2018) as well as the Integrated Carbon Observation System (ICOS, 2020). The test site covers an area of approximately 1 km x 1 km and is located in the ~~lower Rhine valley~~catchment of the Rur river (Bogena et al., 2018). Selhausen had a crop rotation of sugar beet (*Beta vulgaris*), winter wheat (*Triticum aestivum*) and winter barley (*Hordeum vulgare*), fewer times also rapeseed (*Brassica napus*) and potatoes (*Solanum tuberosum*) from 2015 to 2019. Cover crops such as oilseed radish or ~~catch~~ cover crop mixes are planted occasionally between two main crop rotations. Continuous records of meteorological variables, soil specific observations, as well as greenhouse gas and energy fluxes are available for Selhausen since 2011. Regular LAI measurements are available since 2016 (Ney and Graf, 2018).

Merzenhausen (50.93033°N, 6.29747°E) is located at approximately 14 km from Selhausen and is also part of the TERENO Rur Hydrological Observatory. The crop rotation of the site includes sugar beet (*Beta vulgaris*), winter wheat (*Triticum aestivum*), winter barley (*Hordeum vulgare*), rape seed (*Brassica napus*) and occasionally catch cover crop~~s~~ mixes. For Merzenhausen, continuous records of meteorological variables, soil specific observations and energy fluxes are available since 2011 and LAI measurements from 2016 – 2018.

Klingenberg (50.89306°N, 13.52238°E) is an ICOS cropland site located in the mountain foreland of the Erzgebirge that is operated by the Technical University Dresden (TU Dresden) (ICOS, 2020; Prescher et al., 2010). The site is characterized as managed cropland with a 5-year planting rotation of rapeseed (*Brassica napus*), winter wheat (*Triticum aestivum*), maize (*Zea mays*), spring and winter barley (*Hordeum vulgare*) (Kutsch et al., 2010). Since 2004, data on ecosystem fluxes (including net ecosystem and net biome productivity), meteorological variables and soil observations are collected. Furthermore, biomass observations and agricultural management information are available for this site.

The cropland site Lonzée (50.553°N 4.746°E) in Belgium is also part of ICOS (Buysse et al., 2017). It has been planted in a four-year rotation cycle with sugar beet (*Beta vulgaris*), winter wheat (*Triticum aestivum*), potato (*Solanum tuberosum*) ~~, winter wheat (*Triticum aestivum*)~~ since 2000 with Mustard as a cover crop after winter wheat harvest (Moureaux, 2006; Moureaux et al., 2008). For Lonzée, continuous records of meteorological variables, EC flux data and LAI (GLAI and GAI) measurements are available from 2004 onwards. General information on the ICOS study sites such as climatic conditions, soil types etc. is provided on the ICOS Carbon Portal under the respective site codes (ICOS, 2020).

At all sites, the application of mineral fertilizer and herbicides/pesticides as well as occasional application of organic fertilizer is regular management practice.

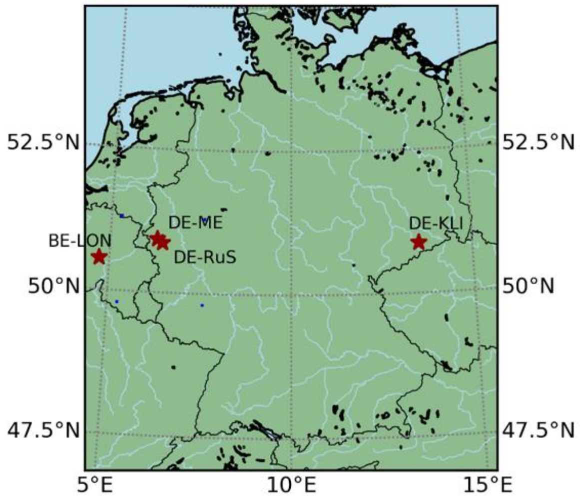


Figure 6: ICOS and TERENO cropland study sites Selhausen (DE-RuS), Merzenhausen (DE-RuM), Klingenberg (DE-Kli) and Lonzée (BE-Lon)

Station data required to force CLM, i.e. meteorological variables (see following section) were measured as block averages over 10 minutes or at higher resolutions, gap-filled using linear statistical relations to nearby stations where possible (Graf, 2017), or otherwise, by marginal distribution sampling within the software package REddyProc (Wutzler et al., 2018). Fluxes required for model validation (i.e. net ecosystem CO_2 exchange (NEE), latent heat flux (LE), sensible heat flux (H), soil heat flux (G) and gross primary production (GPP)) and net radiation (Rn), were either measured (G and R_n) or computed from turbulent raw measurements (frequency ≥ 10 s^{-1}) using the eddy-covariance method, for 30-minute block averages by the site PIs. Subsequently, gaps were filled and GPP estimated from NEE using REddyProc (Wutzler et al., 2018). More details on quality control, filling of longer gaps and by nearby stations, correction of soil heat flux and energy balance closure analysis are given in Graf et al. (*in review*) and specifically for DE-RuS and DE-RuM including LAI measurements in Reichenau et al. (2020). The long-term annual energy balance closures of the sites DE-RuS, DE-Kli and BE-Lon were approximately 79%, 77% and 76%, respectively, according to analyses in Graf et al. (*in review*) and 76% at DE-RuM according to an earlier study by Eder et al. (2015). All half-hourly meteorological and flux data were aggregated to hourly averages to match our ~~the~~ customized CLM forcing time step.

Site-specific measurement records of latent and sensible heat fluxes, net ecosystem exchange (NEE), LAI, soil temperature and soil moisture were used as validation data for the simulation runs.

Forcing variables were always used in gap-filled form, while validation variables were used in un-filled, quality-filtered form.

~~2~~3 Experimental design and analyses

~~2.1~~3.1 Model implementation

For the single point study sites, CLM was run in point mode with only one grid cell and forced with site specific hourly meteorological data.

The annual fertilization amounts at the single point study sites were adjusted according to documented amounts of applied fertilizer that ranged between 12 and 20 gNm^{-2}. In CLM5, the potential photosynthetic capacity as well as the total amount of assimilated carbon during the phenology stages are regulated by the availability of soil nitrogen

(Lawrence et al., 2018). With modern fertilization practices in Europe, nitrogen is not assumed to ~~represent~~ be a limiting factor for the studied sites.

In order to balance ecosystem carbon and nitrogen pools, gross primary production and total water storage in the system, a spin-up is required (Lawrence et al., 2018). An accelerated decomposition spin-up of 600 years and an additional spin-up of 400 years was conducted for each site with the BGC-Crop module ~~active~~ (Lawrence et al., 2018; Thornton and Rosenbloom, 2005). The ~~resulting restart file~~simulated conditions at the end of the spin-up were~~was~~ then used as initial conditions for the following simulations.

~~Table 3: Overview of conducted simulation test runs and scenarios for the three main modifications (1) winter cereal representation, (2) parameterization and (3) cover cropping scheme listing the respective sites, simulation periods, simulated CFTs, number of runs and different model versions and parameterizations that were run. CLM_D indicates the default model version, CLM_WW is the modified winter wheat model, and CLM_WW_CC is the modified winter wheat model extended with the cover cropping subroutine. The options *d* and *m* imply usage of the default or modified parameter set respectively.~~

~~Site~~	~~Simulation year(s)~~	~~Simulated CFT~~	~~Nr. of runs~~	~~Model version~~	~~Parameter set~~
~~**1 Winter cereal representation**~~					
~~DE-RuS~~	~~2017/2018~~	~~Winter wheat~~	~~2~~	~~CLM_D~~ ~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~DE-RuM~~	~~2016/2017~~	~~Winter wheat~~	~~2~~	~~CLM_D~~ ~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~DE-Kli~~	~~2005/2006~~ ~~2010/2011~~ ~~2015/2016~~	~~Winter wheat~~	~~2~~	~~CLM_D~~ ~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~BE-Lon~~	~~2006/2007~~ ~~2008/2009~~ ~~2010/2011~~ ~~2012/2013~~ ~~2014/2015~~ ~~2016/2017~~	~~Winter wheat~~	~~2~~	~~CLM_D~~ ~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~**2 Parameterization**~~					
~~DE-RuS~~	~~2017~~	~~Sugar beet~~	~~2~~	~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~DE-RuS~~	~~2019~~	~~Potato~~	~~2~~	~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~DE-Kli~~	~~2018~~	~~Temperate corn~~	~~1~~	~~CLM_WW~~	~~*d*~~
~~BE-Lon~~	~~2008~~ ~~2016~~	~~Sugar beet~~	~~2~~	~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~BE-Lon~~	~~2010~~ ~~2014~~ ~~2018~~	~~Potato~~	~~2~~	~~CLM_WW~~	~~*d*~~ ~~*m*~~
~~**3 Cover cropping scheme**~~					
~~DE-RuS~~	~~2016 – 2017~~	~~Barley~~ ~~Cover crop 1 – greening mix~~ ~~Potato~~	~~2~~	~~CLM_D~~ ~~CLM_WW_CC~~	~~*d*~~ ~~*m*~~
~~DE-RuS~~	~~2017 – 2019~~	~~Sugar beet~~ ~~Winter wheat~~ ~~Potatoes~~	~~2~~	~~CLM_D~~ ~~CLM_WW_CC~~	~~*d*~~ ~~*m*~~

~~To test the first modification, the implementation of the winter cereal representation, single point simulations were run with the default model version and with the modified model. The default model uses the standard and modified parameter set for winter wheat as input, while the modified model uses the modified parameter set for all winter wheat years. Simulations are performed for DE-RuS, DE-Kli, BE-Lon and DE-RuM (see Table 3). The modified CLM_WW is further used and extended in the subsequent steps.~~ In order to test the winter wheat representation, several simulations were conducted for all winter wheat years at the sites DE-RuS, DE-RuM, DE-Kli and BE-Lon. In a first step, the impact of each modification was assessed individually by simulating one winter wheat year at the site DE-RuS using four different model configurations: (1) the default model and default parameter set (control), (2) the default model with the new parameter set (control + crop specific), (3) the extended winter wheat

model with the default parameter set (new routine), and (4) the extended winter wheat model with the new parameter set (new routine + crop specific). Further evaluations for the other study sites and years were conducted for the combined winter wheat modifications CLM_WW (extended model with winter wheat subroutines and new crop specific parameterization) in comparison to control simulations (default model configuration and default parameterization of winter wheat).
For the evaluation of the crop specific parameter sets for sugar beet and potatoes, simulations were run with the new parameterizations at the sites DE-RuS and BE-Lon over several years. For both sites, control simulations were conducted without the new parameter set, in which both CFTs sugar beet and potatoes are simulated as a spring wheat by default. Furthermore, an evaluation of the default parameterization for the CFT temperate corn at the site DE-Kli is included in the supplementary material (Fig. S1, Table S1).

For testing of the second modification, the parameterization of sugar beet and potatoes, simulations were run with both the default and the modified parameter set for sugar beet and potatoes at the sites DE-RuS and BE-Lon. Furthermore, the default parameterization of the active CFT for corn was tested for the site DE-Kli (Table 3).
The third modification, theThe cover cropping and crop rotation scheme, was tested for two practical cases at Dthe cropland site DE-RuS. From 2016 to 2017, planting was altered at DE-RuS from barley (here represented by the CFT for spring wheat) in 2016 to sugar beet in 2017 with a greening mix cover crop in between (winter months 2016/2017). In order to simulate this common cover cropping practice, we implemented a new CFT for a greening mix cover crop (or $covercrop_1$). For the years 2017 to 2019 at DE-RuS, the subroutines ability to simulate realistic crop rotation cycles was tested by changing the simulated CFT from sugar beet (2017) to winter wheat (2017-2018) and then to potatoes (2019). (Table 3). In this step, the CLM_WW model was further extended with the cover cropping subroutine (CLM_WW_CC) and the sIn this step, simulations were run with the previously modified and tested crop specific parameterizations for sugar beet, potatoes and winter wheat. Simulation results were again compared to a control simulation run, where a consecutive growth of spring wheat is simulated. set of crop specific parameters. CLM_WW_CC simulation results were then compared to default model simulation results (CLM_D) using site specific validation data.

2.23.2 Evaluation of model performance

For statistical evaluation of the model results, the root mean square error (RMSE), the bias (BIAS) and the Pearson correlation (r) were chosen as performance metrics:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - X_{obs,i})^2}, \quad (8)$$

$$BIAS = \sum_{i=1}^{n}(X_i - X_{obs,i}) / \sum_{i=1}^{n}(X_{obs,i}), \quad (9)$$

$$r = (\frac{1}{n}\sum_{i=1}^{n}\left(X_{obs,i} - \mu_{obs}\right) * (* X_i - \mu_{sim}) - \mu_{sim} * \mu_{obs})/(\sigma_{sim} * \sigma_{obs}),$$

(10)

where i is time step and n the total number of time steps, X_i and $X_{obs,i}$ are the simulated and the observed values at every time step with μ_{sim} and μ_{obs} being the respective mean values. The standard deviation of simulation results and measurement data are represented by σ_{sim} and σ_{obs} respectively.
The statistical evaluation was conducted for daily simulation output and daily observation data for the variables NEE, LE, H and Rn.

34 Results

3.14.1 Winter cereal representation

The impact of the new winter wheat specific parameterization and the new winter wheat routine, as well as the combination of both is illustrated in Fig. 2. Here we show simulated LAI for the default model and default parameter set (control), the default model with the new parameter set (control + crop specific), the extended winter wheat model with the default parameter set (new routines) and the extended winter wheat model with the new parameter set (new routines + crop specific).

Using only the new crop specific parameter set with the default model configuration resulted in slightly higher LAI values compared to the control run but did not reach the observed maximum LAI values and the growth cycle duration. The implementation of the winter wheat subroutines using the default parameter set led to a more realistic reproduction of the growth cycle duration compared to the control run, but did not yield good correspondence with observed LAI magnitudes. The combination of the new crop specific parameter set and the new winter wheat subroutines resulted in the most realistic LAI dynamics (Fig. 2). As previously described by Lu et al. (2017), the default vernalization routine reaches a factor of 1 (fully vernalized) shortly after planting when the first frost occurs. This induced an unrealistically early commencement of the grain fill stage within two months after planting in the control run (November or December). The default vernalization also resulted in peak LAI occurring too early in the year, leading to significantly lower photosynthesis compared to the observations. This also applies to the implementation of the new crop-specific parameter set, which generally leads to slightly higher LAI values.

In the extended winter wheat model, the adapted vernalization routine produces lower initial vernalization factors which reduce the growing degree days. This leads to later onset of the leaf emergence and grain fill stage and allows a more realistic representation of the LAI cycle and peak in combination with the new crop specific parameterization.

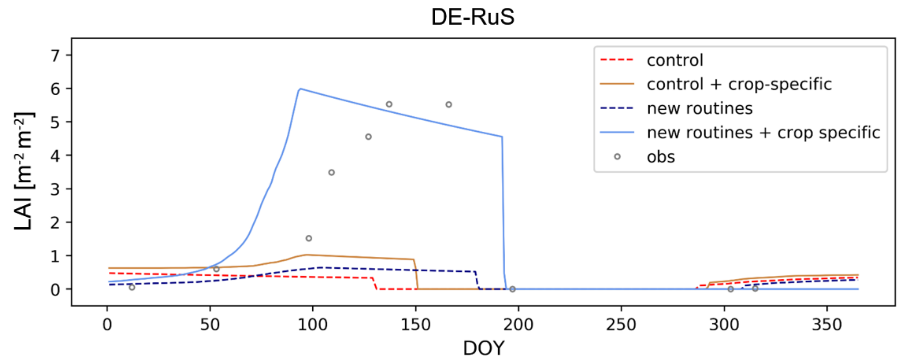


Figure 7: Daily simulation results for the LAI, simulated with default model and the default parameter set (control), the default model with new parameter set (control + crop specific), the extended winter wheat model with default parameterization (new routines) and the extended model with the new parameter set (new routines + crop specific), compared to point observations for a winter wheat year at DE-RuS.

In further evaluations, the combined winter wheat package, including the new crop specific parameterization and the extended winter wheat subroutines is implemented in CLM_WW simulations and compared to control runs (Fig. 3).

For all study sites and simulation years, CLM_WW simulations resulted in a much better representation of the growth cycle and corresponding seasonal LAI variation and magnitudes compared to control with CLM_D simulations (FigureFig.s 2-52-3). Also, the temporal pattern of energy fluxes and NEE were improved with CLM_WW compared to the control run.

In general, CLM_WW yielded LAI peak magnitudes similar to observations at the sites BE-Lon, DE-RuS and DE-RuM (Fig. 3). For DE-Kli, site-specific observations of the LAI were not available, but simulated LAI magnitudes for DE-Kli using CLM_WW are similar to those for BE-Lon. For the BE-Lon site, CLM_WW simulated peak LAI magnitudes are close to the observations. An exception is the year of 2015, where CLM_WW underestimated the unusually high LAI values observed in May and June, which ranged from 5.40 to 6.38 m^2/m^2. For BE-Lon, faster growth was simulated in the early growing stage of winter wheat, resulting in a more gradual increase in LAI compared to the other sites (Figure 3). This is related to higher air temperatures at BE-Lon early in the growing stage (especially in February) that enabled more simulated growth compared to the other sites.

Overall, the LAI peak simulated with CLM_WW occurred about one month earlier than observed, suggesting that maturation was reached too early. This is also reflected in the simulated CLM_WW harvest dates that are approximately one month earlier than the recorded dates (Table 3). While the planting date is the same for the control run and the CLM_WW simulations, CLM_WW generally resulted in a better match of simulated and recorded harvest dates (1.5 to 2 months later than control run).

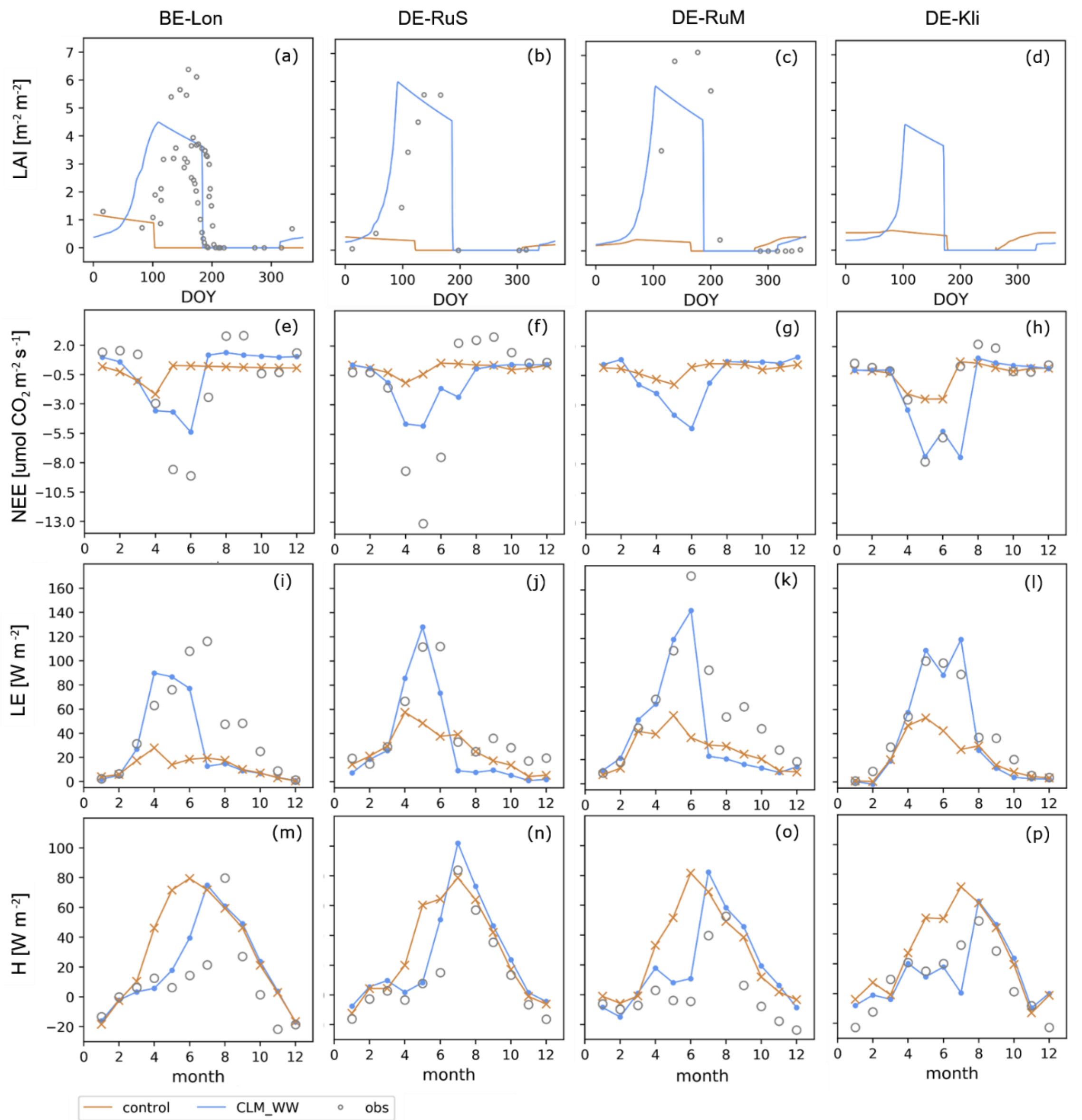


Figure 8: Simulation results of (a-d) LAI and simulation results averaged for each month of (e-h) NEE, (i-l) LE, and (m-p) H for all winter wheat years (see Table 3) at the sites (from left to right) BE-Lon, DE-RuS, DE-RuM and DE-Kli. Simulation results from the new routine with crop specific parameterization – CLM_WW (blue) are compared to control simulations (orange) and available site observations (grey) of LAI (all available point observations plotted) and fluxes (averaged over all respective years and for each month respectively). Corresponding performance statistics for daily simulation results during the crop growth cycle are listed in Table 4.

As described by Lu et al. (2017), the default vernalization routine reaches a factor of 1 (fully vernalized) shortly after planting when the first frost occurs. This induced an unrealistically early commencement of the grain fill stage within two months after planting (November or December). The peak in LAI in the default version is also reached early in the year where photosynthesis is generally lower. The adapted CLM_WW vernalization routine produces lower initial vernalization factors which reduce the growing degree days. This leads to later onset of the leaf emergence and grain fill stage, in line with observations for all simulated study sites and years (Figures 2-5). While the planting date is the same for CLM_D and CLM_WW simulations, CLM_WW generally resulted in a better match of simulated and recorded harvest dates, compared with CLM_D simulations (1.5 to 2 months later than CLM_D), but harvest is still simulated slightly too early for all sites (Table 4).

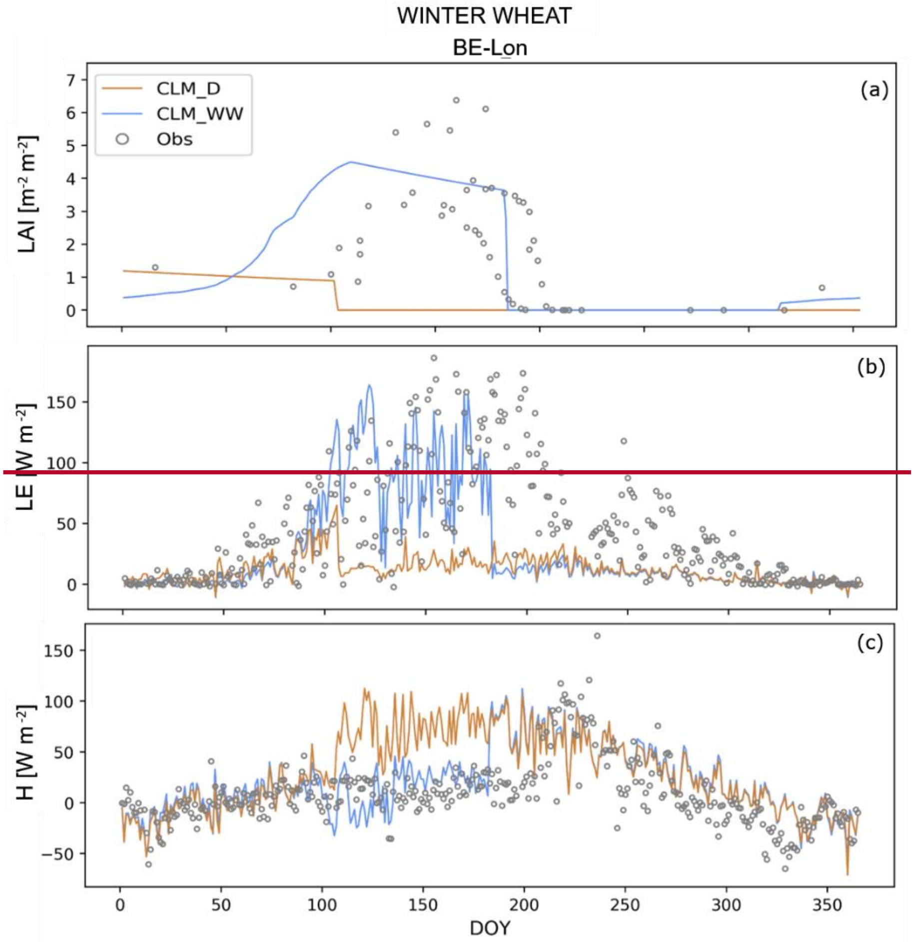


Figure 2: Daily simulation results of (a) LAI, (b) LE and (c) H averaged over all winter wheat years (see Table 5) at the BE-Lon site. Simulations were run with the default model version (CLM_D) indicated in orange and the modified model version (CLM_WW) indicated in blue. Site observation data on GLAI (all available observations plotted) and fluxes (averaged over all respective years) are indicated in grey. Corresponding performance statistics for daily simulation results are listed in Table 5.

For the BE-Lon site, CLM_WW simulated average LAI peak magnitudes, as well as seasonal LAI variations, are close to the observations of the green leaf area index (GLAI), with the exception of 2015, where unusually high GLAI values where observed in May and June, ranging from 5.40 to 6.38 m^2/m^2. The LAI peak of CLM_WW happens approximately one month too early compared to observations, and thus, the maturity of the crop is reached too early. This is also reflected in CLM_WW planting and harvest dates that are simulated approximately 1 month earlier than recorded dates. The correlation of simulated grain yield and site records was significantly improved by up to 87 % in CLM_WW simulations compared to the control run. At the DE-RuS site, CLM_WW resulted in a grain yield of 9.15 t/ha that is very close to the observed value of 9.2 t/ha, while grain yield is strongly underestimated in the control run (1.17 t/ha). For DE-Kli, the CLM_WW simulated crop yield matched the recorded yield data very well for the year 2016 and was overestimated for 2011 by approximately 16 %. The control run resulted in an underestimation of yield by more than 80 % (Fig. 4, Table 3). The CLM_WW simulated latent heat flux is underestimated after the crop cycle has ended in simulations compared to actual field conditions, where the crop is harvested later and thus more latent heat is generated on the field (Table 4, Figure 2). Although simulated maximum LAI generally correspond reasonable with observed valuesFor BE-Lon , the resulting simulated crop yield is underestimated compared to site harvest records (Fig. 4, Table 43). While CLM_D simulations underestimated the grain yield by approximately 85 – 90 %, CLM_WW underestimated yield by only 18 - 36 % at BE-Lon. The simulated yields by CLM_WW for the individual years show only minimal variations with values from 8.12 to 8.16 t/ha, while the measured yields ranged from 9.92 to 12.88 t/ha, indicating that CLM did not capture the inter-annual yield variation very well (Table 3).The CLM_WW simulated yields show only minimal variations with values from 8.12 to 8.16 t/ha whereas measured yields range from 9.92 to 12.88 t/ha. Therefore, CLM_WW did not capture the inter-annual differences in yield very well (Table 4).

As observed for the BE-Lon site, CLM_WW overestimated early growing season LAI at the DE-RuS and DE-RuM sites with the simulated peak and subsequent slow decline in LAI happening earlier than observed values (Figure 3 and 4). At the DE-RuS site, the generally good correspondence in growing cycle and LAI of the CLM_WW simulation is also reflected in the resulting crop yield of 9.15 t/ha that is very close to the observed value of 9.2 t/ha, while CLM_D strongly underestimated yield (1.17 t/ha).

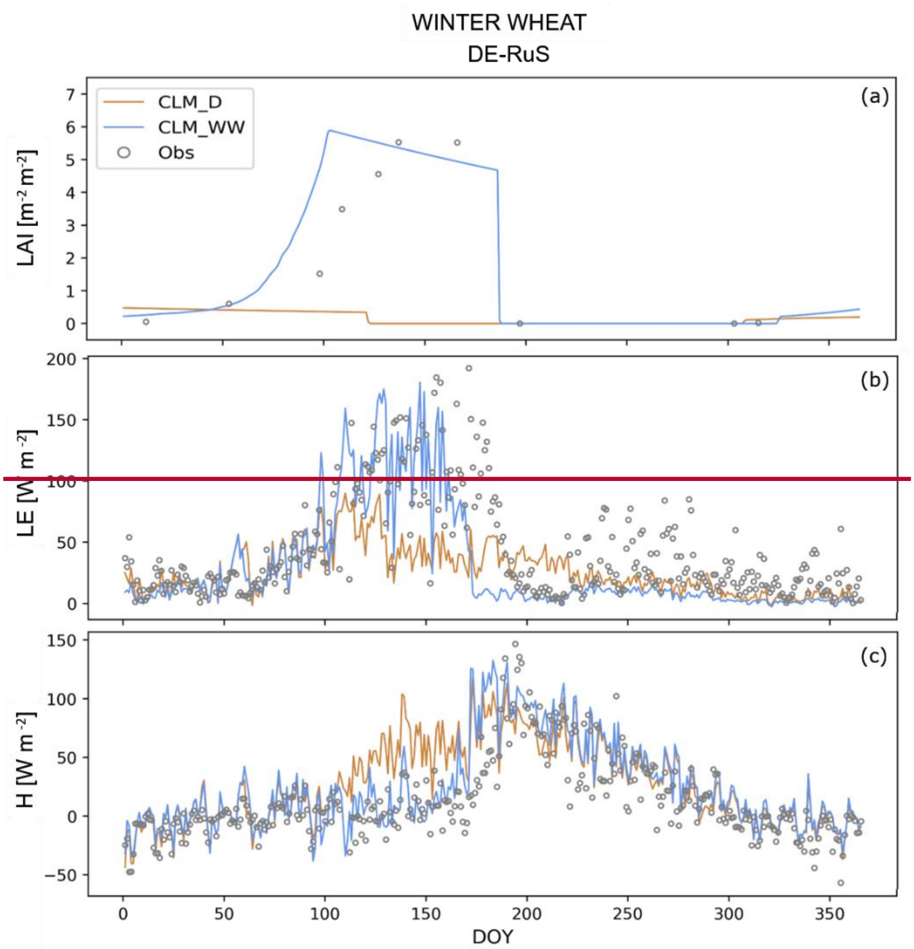


Figure 3: Daily simulation results of (a) LAI, (b) LE and (c) H for the winter wheat year 2018 at the DE-RuS site. Simulations were run with the default model version (CLM_D) indicated in orange and the modified model version (CLM_WW) indicated

in blue. Site observation data on LAI (all available observations plotted) and fluxes (averaged over all respective years) are indicated in grey. Corresponding performance statistics for daily simulation results are listed in Table 5.

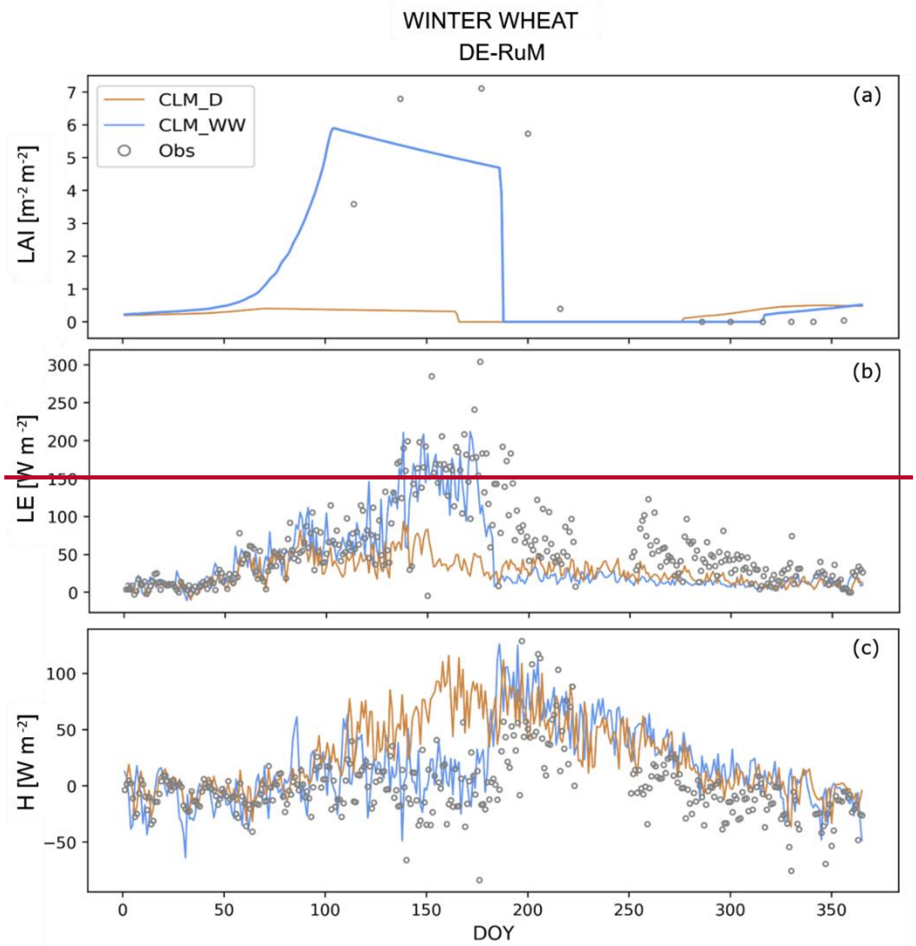


Figure 4: Daily simulation results of (a) LAI, (b) LE and (c) H for the winter wheat year 2017 at the DE-RuM site. Simulations were run with the default model version (CLM_D) indicated in orange and with the modified model version (CLM_WW) indicated in blue. Site observation data on LAI (all available observations plotted) and fluxes (averaged over all respective years) are indicated in grey. Corresponding performance statistics for daily simulation results are listed in Table 5.

For the DE-Kli site (Figure 5), site specific observations of the LAI are not available. However, CLM_WW resulted in much more realistic magnitudes of LAI than CLM_D simulations. The generally lower LAI peak of CLM_WW compared to the other two sites is also reflected in lower crop yields for DE-Kli. Here, CLM_WW simulated crop yields match recorded yield data very well for the year 2011 and are overestimated for 2016 by approximately 16 %. CLM_D resulted in an underestimation of yield by more than 80 %.

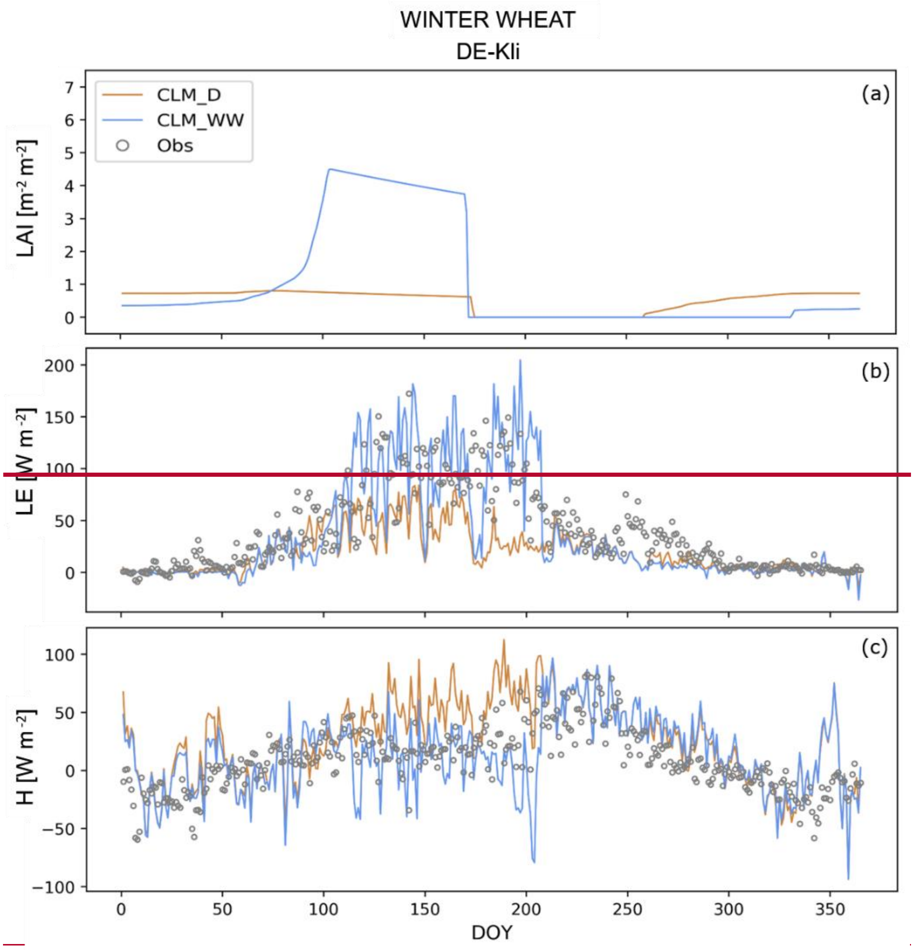
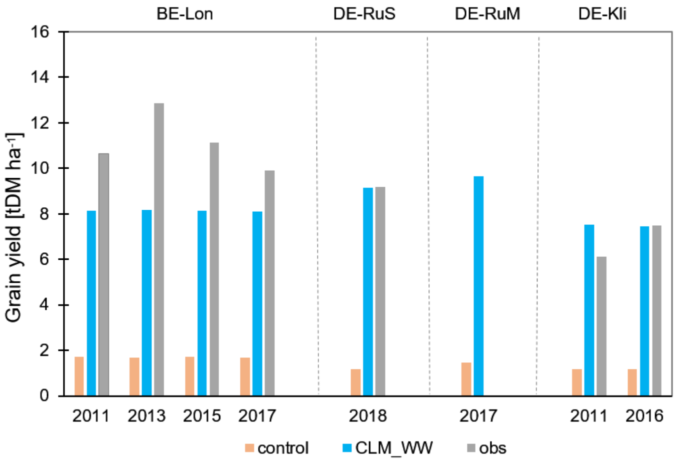


Figure 5: Daily simulation results of (a) LAI, (b) LE and (c) H averaged over all winter wheat years (see Table 5) at the DE-Kli site. Simulations were run with the default model version and the default parameter set (CLM_D) indicated in orange and the modified model version (CLM_WW) indicated in blue. Site observation data on LAI (all available observations plotted) and fluxes (averaged over all respective years) are indicated in grey. Corresponding performance statistics for daily simulation results are listed in Table 5.

The generally better representation of the winter wheat growing cycle by CLM_WW is also reflected in simulated NEE (Figure 6) and surface energy fluxes (Figures 2-5). In terms of net radiation, both CLM_WW and CLM_D are very close to the observations (Table 5). However, CLM_WW was able to better capture seasonal variations in cumulated monthly sums of surface energy fluxes during the growing cycle of the crop. The correlation coefficients for the energy fluxes (LE, H and Rn) calculated over the timeframe from recorded planting to harvest date (Table 4) improved for all sites (Table 5). Highest correlations were reached for the sites DE-Kli with r values of 0.62 and 0.71 and for BE-Lon with r values of 0.5 and 0.46 for sensible heat and latent heat flux respectively (Table 5). While the correlation of these variables is generally increased with the CLM_WW model, latent and sensible heat flux RMSE and biases are still relatively high, especially for the BE-Lon site, with corresponding low correlations. The high latent heat flux measured at BE-Lon in the later months of the year (from day 220 onwards) reflects a second growth cycle of a cover crop. At both the BE-Lon site as well as at the DE-Kli site, catch crops are typically sown after harvest of winter wheat (mustard at BE-Lon, radish and brassica at DE-Kli)

~~which strongly effects surface energy fluxes later in the year, whereas in CLM, the crop field is simulated as fallow~~



~~(Figures 2 and 5).~~

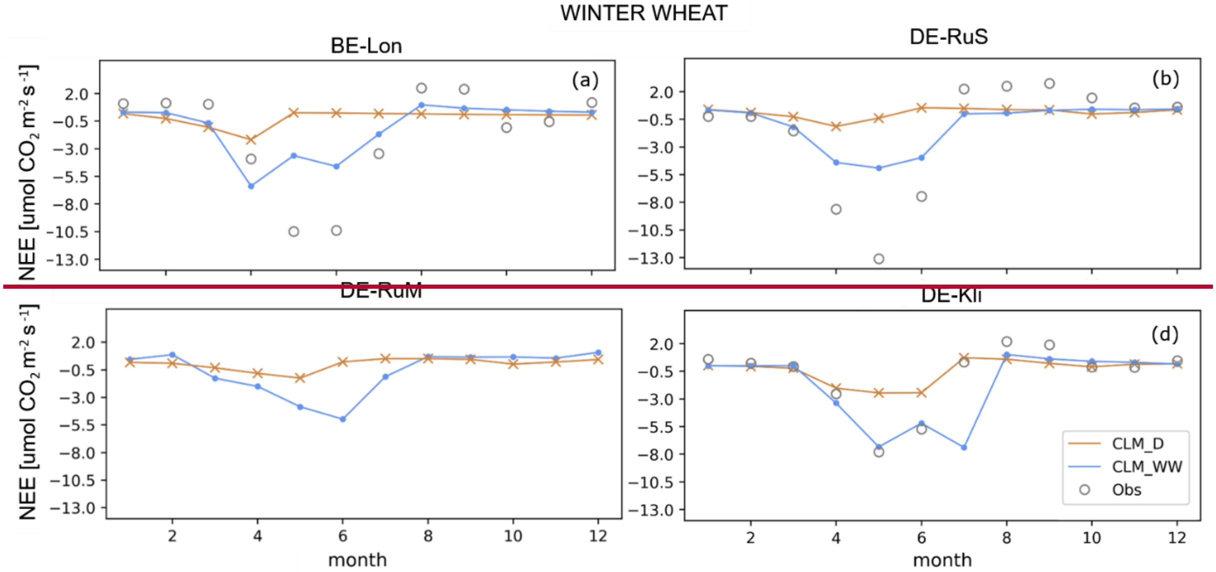
Figure 9: Annual grain yield [tDM/ha] simulated with the control run (orange) and the extended winter wheat model with crop specific parameterization (blue), compared to recorded harvest yields (grey) for all simulated winter wheat years (indicated on the x axis) at the sites BE-Lon, DE-RuS, DE-RuM and DE-Kli.

Table 3: Simulated annual planting and harvest dates and grain yield [tDM/ha] by CLM_WW and CLM_D simulations (calculated using the peak daily grain carbon throughout the growth cycle) compared to recorded harvest dates and grain yield (Obs) for all simulated winter wheat years at the sites BE-Lon, DE-RuS, DE-RuM and DE-Kli. For CLM simulation results, grain yield is calculated from grain carbon which is assumed to be 45 % of the total dry weight.

Year	Source	Planting date	Harvest date	Grain Yield [tDM/ha]
		BE-Lon		
	CLM_D	11.09.2010	10.05.2011	1.71
2010/2011	CLM_WW	11.09.2010	05.07.2011	8.14
	Obs	*14.10.2010*	*16.08.2011*	*10.64**
	CLM_D	12.09.2012	19.04.2013	1.68
2012/2013	CLM_WW	12.09.2012	25.06.2013	8.16
	Obs	*25.10.2012*	*12.08.2013*	*12.88*
	CLM_D	09.09.2014	20.04.2015	1.71
2014/2015	CLM_WW	09.09.2014	01.07.2015	8.15
	Obs	*15.10.2014*	*02.08.2015*	*11.13*
	CLM_D	11.09.2016	02.05.2017	1.68
2016/2017	CLM_WW	11.09.2016	24.07.2017	8.12
	Obs	*29.10.2016*	*30.07.2017*	*9.92*
		DE-RuS		
	CLM_D	29.09.2017	17.05.2018	1.17
2017/2018	CLM_WW	29.09.2017	27.06.2018	9.15
	Obs	*25.10.2017*	*16.07.2018*	*9.2*
		DE-RuM		
	CLM_D	27.09.2016	15.05.2017	1.45
2016/2017	CLM_WW	27.09.2016	30.06.2017	9.65
	Obs	*17.10.2016*	*22.07.2017*	-
		DE-Kli		
	CLM_D	15.09.2009	23.07.2011	1.19
2010/2011	CLM_WW	15.09.2009	11.08.2011	7.53
	Obs	*02.10.2010*	*22.08.2011*	*6.12*
	CLM_D	17.09.2015	24.07.2016	1.17
2015/2016	CLM_WW	17.09.2015	28.07.2016	7.44
	Obs	*18.09.2015*	*24.08.2016*	*7.48*

*: Grain yield estimated from 18.09 t/ha total biomass (stem and ear) yield according to stem and ear (grain) biomass yield ratios measured for other winter wheat years at the same site.

~~CLM_WW was generally better able to match NEE observations compared to CLM_D due to the better representation of the seasonal LAI variations (Figure 6). Correlation improved (comparing CLM_WW to CLM_D) from 0.13 to 0.46 for BE-Lon, from 0.21 to 0.33 for DE-RuS and from 0.29 to 0.56 for DE-Kli. The resulting correlation for CLM_WW simulations is still relatively low due to an underestimation of the cumulative monthly NEE during seasons with high NEE at both sites. For DE-Kli, CLM_WW was able to match NEE observed at peak LAI very well. However, late seasonal NEE (July), shortly before harvest, is overestimated by CLM_WW resulting in a low overall agreement with observation data.~~



~~Figure 6: Comparison of (orange) CLM_D and (blue) CLM_WW simulated monthly NEE rates at the sites (a) BE-Lon, (b) DE-RuS, (c) DE-RuM and (d) DE-Kli for all respective winter wheat years. Available site observations are plotted as grey circles. For the sites BE-Lon and DE-Kli, simulation results as well as observation data is averaged over all simulated winter wheat years.~~

Table 4: Bias, root mean square error (RMSE) and Pearson correlation coefficient (r) for the control run~~CLM_D~~ and CLM_WW simulated daily NEE [umol CO_2 W m^{-2} s^{-1}], LE [W m^{-2}], H [W m^{-2}] and Rn [W m^{-2}] at the sites BE-Lon, DE-RuS, DE-RuM and DE-Kli respectively. Values were calculated ~~for the time~~over the time period between recorded planting and harvest dates (averaged over all winter wheat years at each site) using simulation output and observation data at daily time step.

CFT	**WINTERWHEAT**							
Site	**BE-Lon**		**DE-RuS**		**DE-RuM**		**DE-Kli**	
Year(s)	2010/2011 2012/2013 2014/2015 2016/2017		2017/2018		2016/2017		2010/2011 2015/2016	
Model	*control*	*CLM_WW*	*control*	*CLM_WW*	*control*	*CLM_WW*	*control*	*CLM_WW*
				NEE				
Bias	-0.87	-0.37	-1.01	-0.61	-	-	-0.56	0.50
RMSE	6.34	4.96	7.73	7.58	-	-	3.80	3.27
r	-0.13	0.46	0.21	0.33	-	-	0.29	0.56
				LE				
Bias	-0.72	-0.13	-0.47	-0.23	-0.55	-0.09	-0.47	-0.77
RMSE	61.96	50.73	52.47	52.65	67.17	48.67	44.64	56.75
r	0.35	0.46	0.21	0.24	0.50	0.67	0.61	0.71
				H				
Bias	5.56	1.35	4.24	1.70	-8.49	-2.74	4.99	3.10
RMSE	45.97	27.63	40.93	39.94	47.26	32.81	49.30	35.08
r	0.42	0.50	0.45	0.48	0.21	0.36	0.47	0.63
				Rn				
Bias	-0.18	-0.05	-0.17	-0.13	-0.09	0.08	-0.03	-0.09
RMSE	36.11	38.01	47.28	45.15	37.34	46.43	45.17	44.49
r	0.80	0.81	0.68	0.69	0.78	0.97	0.71	0.73

Overall, the better representation of the winter wheat growing cycle by CLM_WW can also be inferred from the simulated surface energy fluxes (Fig. 3). In terms of net radiation, both CLM_WW and the control run are very close to the observations (Table 4). However, CLM_WW was able to better capture seasonal variations of surface energy fluxes during the growing cycle of the crop (Fig. 3). The correlation coefficients for the energy fluxes (LE, H and Rn) calculated over the period from planting to harvest date for daily simulation results and daily observation data improved for all sites (Table 4). Highest correlations were reached for the sites DE-Kli with r values of 0.62 and 0.71 and for BE-Lon with r values of 0.5 and 0.46 for sensible heat and latent heat flux respectively (Table 4). Due to the simulated LAI peak being too early, latent heat flux is underestimated by CLM_WW (Fig. 3, Table 4). The high latent heat fluxes measured at BE-Lon and DE-Kli in the later months of the year (from day 220 onwards) reflect the growth of a cover crop. At both the BE-Lon site as well as at the DE-Kli site, cover crops are typically sown after harvest of winter wheat (mustard at BE-Lon, radish and brassica at DE-Kli), and they strongly affect surface energy fluxes later in the year. In contrast, in the control simulations, as well as in CLM_WW, the crop field were simulated as fallow after the harvest of winter wheat (Fig. 3, Table A1). While the correlation of the latent and sensible heat flux during the growing cycle of the crop is generally increased with the CLM_WW model, the overall annual correlation is still relatively poor due to the influence of cover cropping and poor representation of post-harvest field conditions (annual performance metrics are included in the supplementary material, Table S3). Furthermore, CLM_WW was generally better able to match NEE observations compared to control runs, partly due to the better representation of the seasonal LAI variations (Fig. 3). During the growing season of winter wheat, the negative peak in NEE, coincides with the peak in LAI. Negative NEE values indicate a carbon sink and happen when the crop gains more carbon through photosynthesis than is lost through respiration. Correlation improved (comparing CLM_WW to the control run) from 0.13 to 0.46 for BE-Lon, from 0.21 to 0.33 for DE-RuS and from 0.29 to 0.56 for DE-Kli. The resulting correlation for CLM_WW simulations is still relatively low due to an underestimation of the cumulative monthly NEE during seasons with high NEE at BE-Lon and DE-RuS. For DE-Kli, CLM_WW was able to match NEE observed at peak LAI very well, but late seasonal NEE (July), shortly before harvest, is overestimated by CLM_WW resulting in a low overall agreement with observation data. Furthermore, post-harvest field observations at BE-Lon, DE-RuS and DE-Kli indicate that heterotrophic respiration from soil organic matter and litter results in a carbon source which is not simulated well in CLM (no GPP, near zero NEE) (Fig. 3). This poor representation of post-harvest field conditions is reflected in low correlations over the whole year (Table S3).

3.24.2 Crop specific Pparameterization -of sugar beet and potatoes

~~In order to test the new parameter sets, CLM_WW was used. Since the modifications made in CLM_WW do not affect the considered CFTs (i.e. corn, sugar beet and potatoes), the findings discussed in this section result solely from the usage of modified parameterization.~~

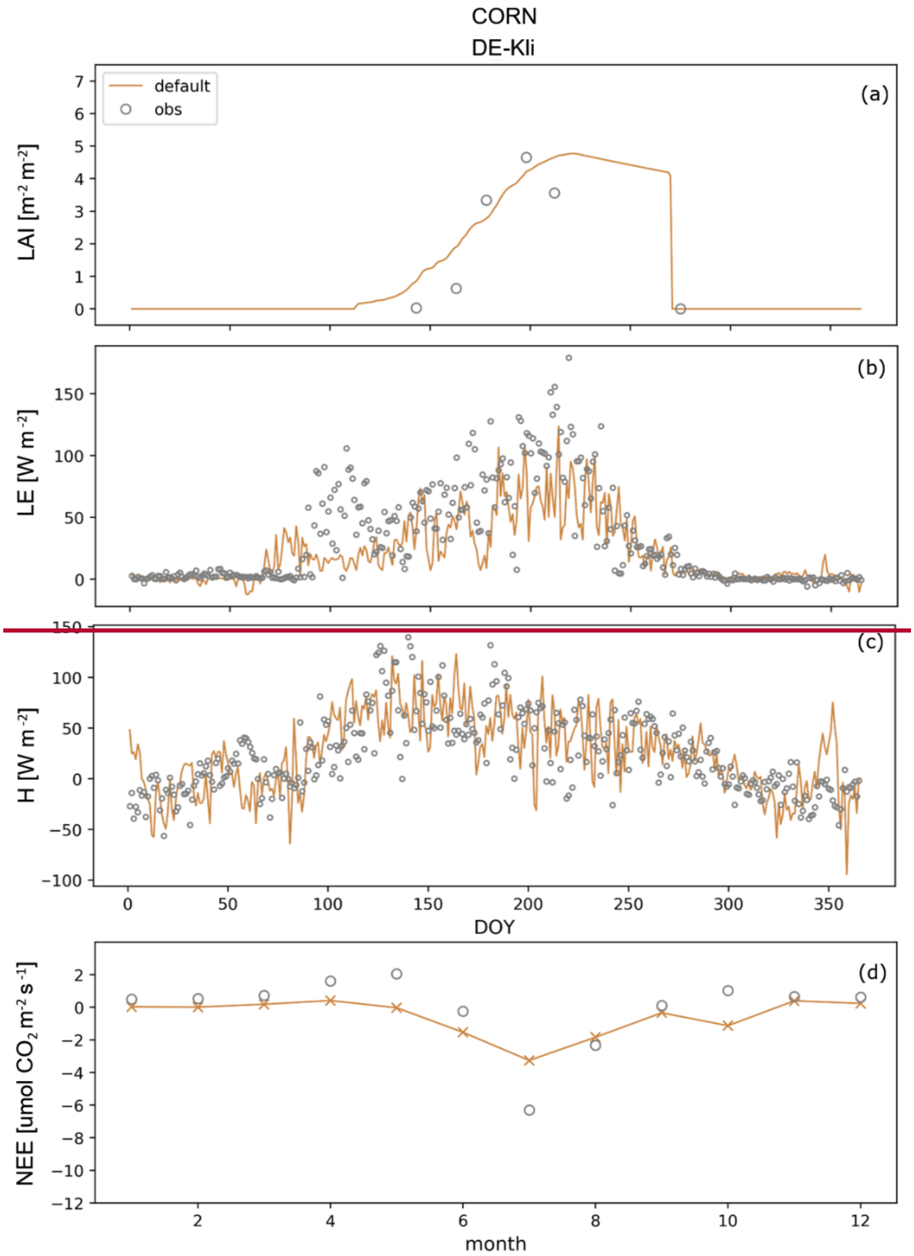
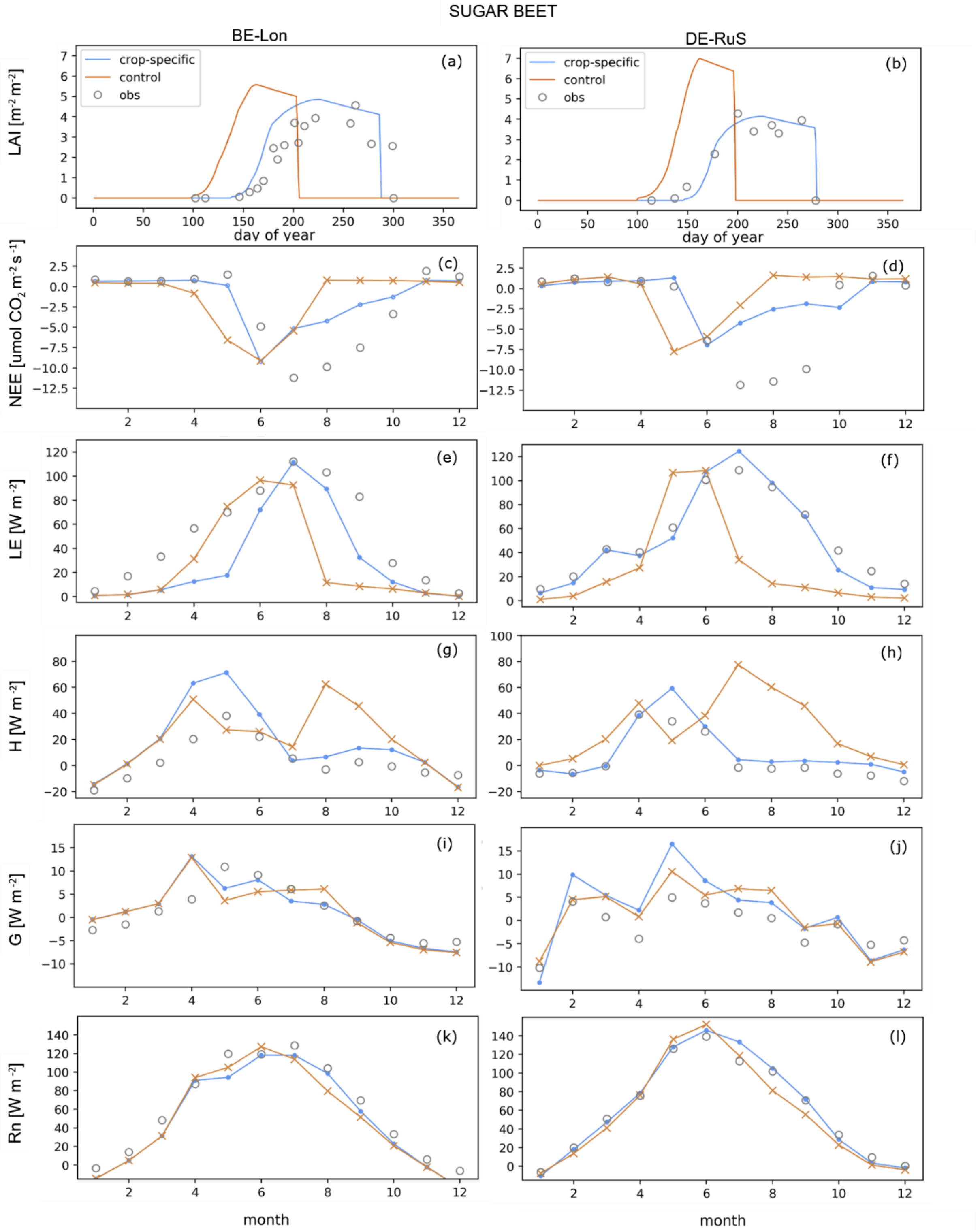


Figure 7: Daily simulation results of (a) LAI, (b) LE, (c) H, and (d) monthly NEE rates averaged over all corn years (see Table 6) at DE-Kli using the default parameterization (orange). Site observation data on LAI (all available observations plotted) and fluxes (averaged over all respective years) are indicated in grey. Corresponding statistical analysis is listed in Table 6.

There is already a specific set of parameters available for the CFT temperate corn. This parameterization was tested for the site DE-Kli, where it resulted in a reasonable representation of seasonal LAI variation and magnitude (Figure 7). A moderate correlation was obtained for latent heat flux (0.56), with underestimation of latent heat flux during the early growing cycle of corn, as well as for sensible heat flux (0.41). Similar to winter wheat at BE-Lon and DE-RuS, the simulated NEE shows a negative bias with an underestimation of peak NEE (Figure 7, Table 6). For the CFTs sugar beet and potatoes, the modified The crop specific parameter sets were was tested for several years with sugar beet and potatoes planting at BE-Lon and DE-RuS respectively. The performance in reproducing seasonal variations and magnitudes of energy fluxes was strongly improved with the modified crop specific parameter setparameterization. Correspondingly, simulations with the crop specific modified parameter sets for both sugar beet and potatoes were able to reasonably capture seasonal variations and peak values of LAI as well as growth cycle length and harvest time (~~Figure~~Figs. ~~8~~5, ~~and~~ Fig. ~~9~~6). The control run in CLM uses the spring wheat parameterization for these crop types and therefore reproduced the growth cycle and seasonal LAI of spring wheat, while simulations using the crop-specific potato and sugar beet parameterizations better captured harvest date and growth cycle of these crops.~~Whereas the default parameterization effectively reproduced the growth cycle and seasonal LAI variation of spring wheat, simulation results from the modified parameterizations better captured harvest date and growth cycle.~~

The improved growth cycle representation with crop specific ~~modified~~ parameters also led to more accurate simulation of energy fluxes. For sugar beet at BE-Lon, the latent heat flux at peak LAI corresponds well with observed values while being underestimated before and after peak LAI and hence the sensible heat flux is overestimated at these times (~~Figure~~Fig. ~~8~~5). Seasonal variations of energy fluxes and magnitudes were also captured much better in simulations with the ~~modified~~ new parameterization. The simulations with crop specific ~~modified~~ parameters show slightly better net radiation correlations for both the sugar beet and potato CFTs at each site, compared to ~~simulations with default parameters~~the control run (Table ~~6~~5). The correlation between simulated and observed latent heat flux for sugar beet were strongly improved by changing the parameters (0.11 to 0.55 for DE-RuS and 0.21 to 0.55 for BE-Lon). The same is true for the simulated sensible heat flux for sugar beet (0.04 to 0.76 for DE-RuS and 0.08 to 0.51 for BE-Lon site). The NEE for the sugar beet CFT is underestimated during peak LAI periods ~~for~~ in the ~~default parameterization~~control run, resulting in poorer correlations compared to latent and sensible heat flux and net radiation (~~Figure~~Fig. ~~8~~5). Simulations with the crop specific ~~modified~~ parameter set resulted in a reduction in negative bias for NEE and reached higher correlation compared to the ~~default parameterization~~control simulation (0.03 to 0.37 for DE-RuS and 0.05 to 0.64 for BE-Lon).

~~Similar improvements can be observed for the new potato parameterization while the correlation of simulation results with observation data is generally lower compared to the sugar beet CFT (Table 6). Seasonal LAI variations, growing cycle length and corresponding energy flux variations are improved in simulations with the modified parameter set. Both the latent and the sensible heat flux are strongly improved at DE-RuS with correlation coefficients of 0.54 and 0.45 respectively for CLM_WW simulations. For BE-Lon, the improvement in correlation is slightly lower for both latent and sensible heat flux compared to DE-RuS. The seasonal variation of the NEE at BE-Lon is reasonably captured while monthly sums are overestimated with both parameterizations. The modified parameter set performed slightly better with an improved correlation of 0.58 compared to 0.43 with default parameterization (Table 6).~~



SUGAR BEET
BE-Lon
DE-RuS
crop-specific
control
obs
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
LAI [m-2 m-2]
NEE [umol CO2 m-2 s-1]
LE [W m-2]
H [W m-2]
G [W m-2]
Rn [W m-2]
day of year
month

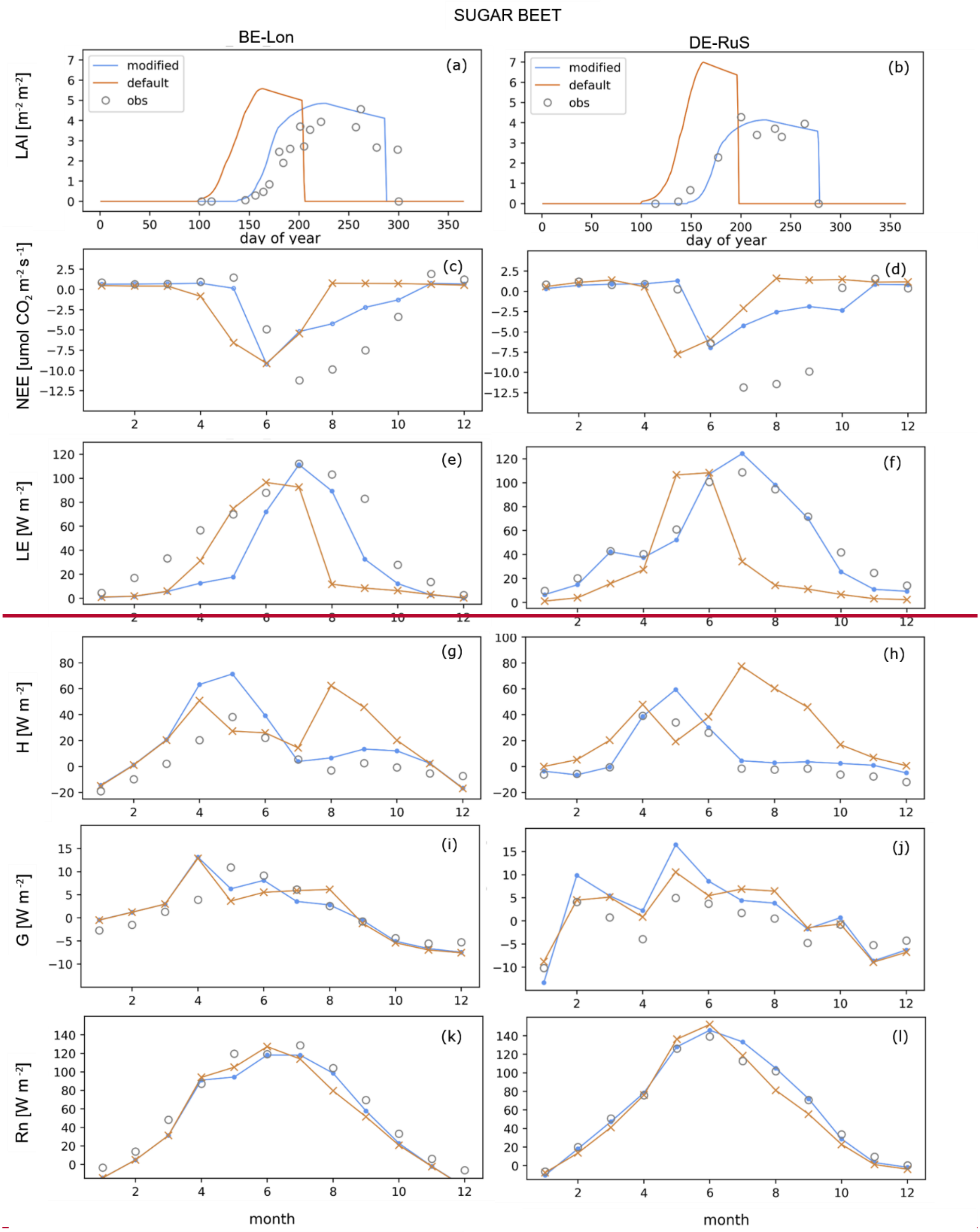
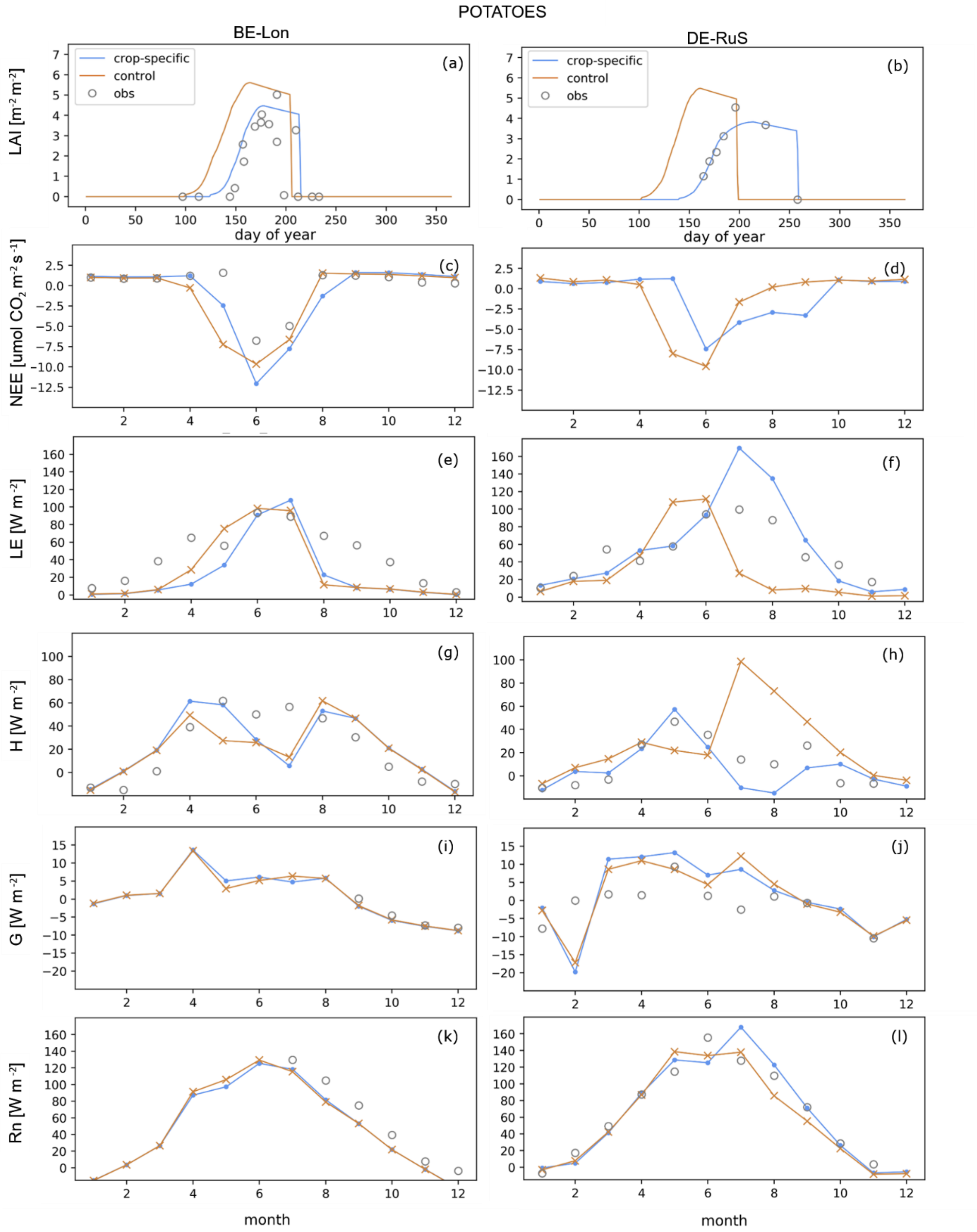


Figure 10: Simulation results of (a-b) LAI and monthly averaged simulation results of (c-d) NEE, (e-f) LE, (g-h) H, (i-j) G and (k-l) Rn for all sugar beet years (see Table 65) at the sites (left) BE-Lon and (right) DE-RuS. Simulation results for the default parameter secontrol run t (orange) and the crop specific modified parameter set (blue) are compared to available site observations (grey) of LAI (all available point observations plotted) and fluxes (averaged over all respective years). Corresponding performance statistics for daily simulation results are listed in Table 65.



POTATOES
BE-Lon
DE-RuS
crop-specific
control
obs
LAI [m-2 m-2]
day of year
NEE [umol CO2 m-2 s-1]
LE [W m-2]
H [W m-2]
G [W m-2]
Rn [W m-2]
month
(a)
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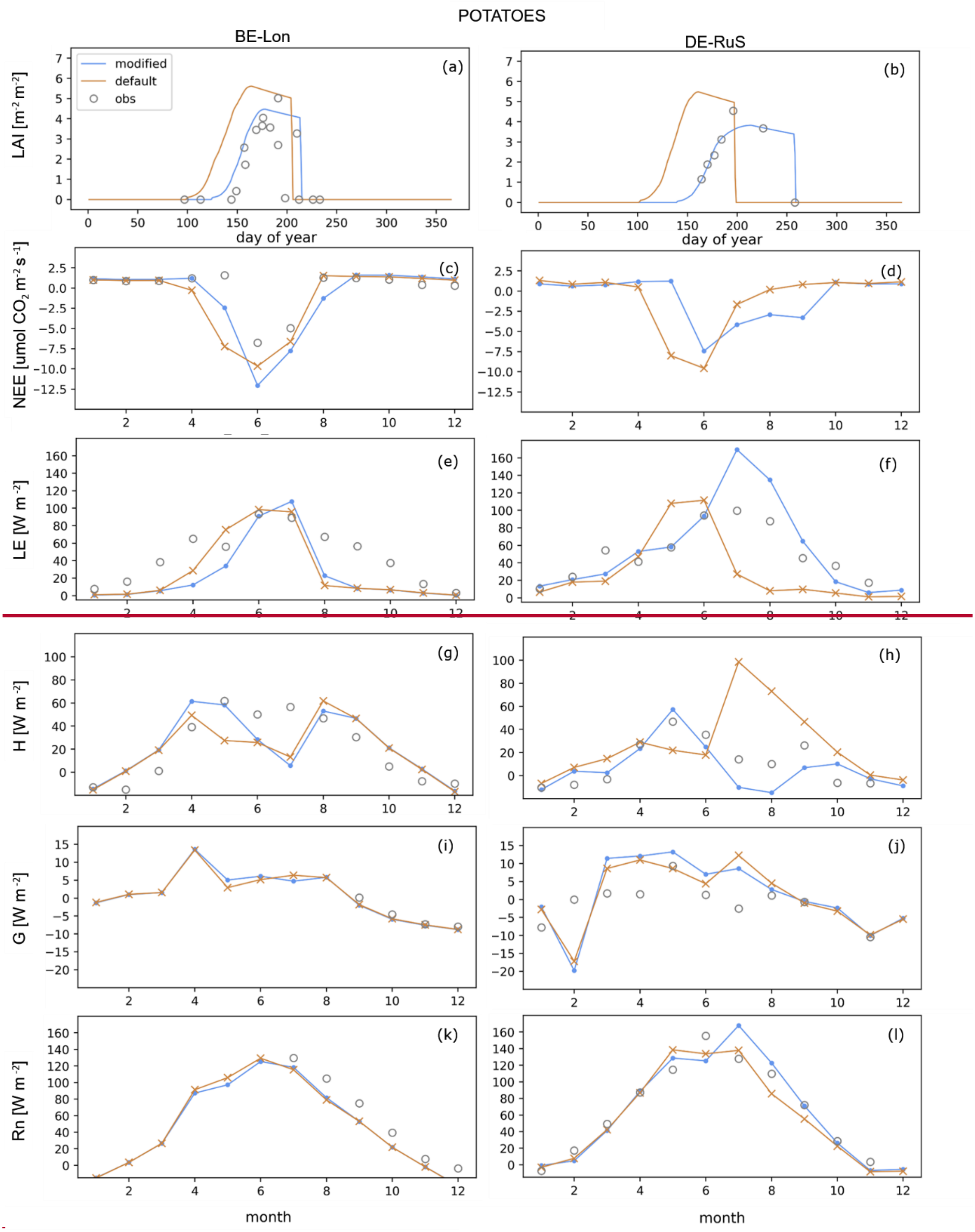


Figure 11: Simulation results of (a-b) LAI and monthly averaged simulation results of (c-d) NEE, (e-f) LE, (g-h) H, (i-j) G and (k-l) Rn for all potatoes years (see Table 5~~6~~) at the sites (left) BE-Lon and (right) DE-RuS. Simulation results ~~run with the default parameter set~~for the control run (orange) and the crop specific ~~modified~~ parameter set (blue) are compared to available site observations (grey) of LAI (all available observations plotted) and fluxes (averaged over all respective years). Corresponding performance statistics for daily simulation results are listed in Table ~~6~~5.

Similar improvements can be observed for the new potato parameterization while the correlation of simulation results with observation data is generally lower compared to the sugar beet CFT (Fig.6, Table 5). Seasonal LAI variations, growing cycle length and corresponding energy flux variations are improved in simulations with the new parameter set. Both the latent and the sensible heat flux are strongly improved at DE-RuS with correlation coefficients of 0.54 and 0.45 respectively for CLM_WW simulations. For BE-Lon, the improvement in correlation is slightly lower for both latent and sensible heat flux compared to DE-RuS. The seasonal variation of the NEE at BE-Lon is reasonably captured while monthly sums are overestimated with both parameterizations. Simulations of the NEE using the crop specific parameter set yielded a slightly better correlation of 0.58 compared to the control simulation that resulted in a correlation of 0.43 (Table 5).

Table 5: Bias, root mean square error (RMSE) and Pearson correlation coefficient (r) for the simulated daily NEE [µmol CO_2 W m^{-2} s^{-1}], LE [W m^{-2}], H [W m^{-2}] and Rn [W m^{-2}] ~~using the default (*d*)~~ ~~and~~ using the ~~modified~~ crop specific parameterization (*specific*~~*m*~~) for the CFTs ~~corn (only default),~~ sugar beet and potatoes at the sites BE-Lon and~~,~~ DE-RuS~~, DE-RuM and DE-Kli~~ respectively. Results are compared to those from the control simulation runs (*control*). Values were calculated over the time period ~~for the time~~ between recorded planting and harvest dates (averaged over all respective CFT years at each site) using simulation output and observation data at daily time step.

CFT	**SUGARBEET**				**POTATOES**			
Site	**DE-RuS**		**BE-Lon**		**DE-RuS**		**BE-Lon**	
Year(s)	2017		2008 2016		2019		2010 2014 2018	
Parameter set	*control*	*specific*	*control*	*specific*	*control*	*specific*	*control*	*specific*
				NEE				
Bias	-0.59	-0.75	0.05	-0.05	-	-	19.73	19.56
RMSE	9.1	5.94	6.19	3.75	-	-	5.24	5.21
r	-0.03	0.37	0.05	0.64	-	-	0.43	0.58
				LE				
Bias	-0.32	0.01	-0.37	-0.35	-0.28	0.25	0.26	0.09
RMSE	58.44	24.47	60.09	48.31	60.94	50.58	43.41	40.05
r	0.11	0.55	0.21	0.55	0.01	0.54	0.5	0.53
				H				
Bias	1.65	0.45	1.73	1.61	1.01	-0.38	0.5	0.22
RMSE	42.77	17.24	39.75	33.45	51.61	29.9	34.06	31.17
r	-0.04	0.76	-0.08	0.51	-0.1	0.45	0.18	0.31
				Rn				
Bias	-0.02	0.04	-0.11	-0.11	-0.04	0.04	-	-
RMSE	19.74	15	37.47	35.87	48.39	49.88	-	-
r	0.5	0.51	-0.22	-0.22	0.56	0.57	-	-

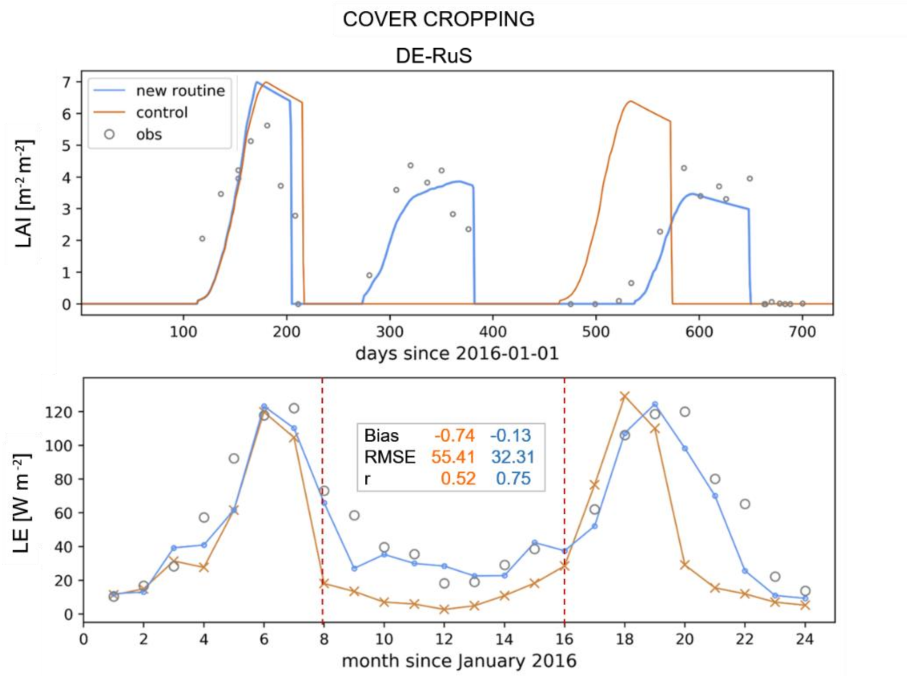
~~CFT~~	~~CORN~~	~~SUGARBEET~~				~~POTATOES~~			
~~Site~~	~~DE-Kli~~	~~DE-RuS~~		~~BE-Lon~~		~~DE-RuS~~		~~BE-Lon~~	
~~Year(s)~~	~~2007~~	~~2017~~		~~2008 2016~~		~~2019~~		~~2010 2014 2018~~	
~~Parameter set~~	~~d~~	~~d~~	~~m~~	~~d~~	~~m~~	~~d~~	~~m~~	~~d~~	~~m~~
~~NEE~~									
~~Bias~~	~~-1.00~~	~~-0.59~~	~~-0.75~~	~~0.05~~	~~-0.05~~	~~-~~	~~-~~	~~19.73~~	~~19.56~~

~~RMSE~~	~~2.59~~	~~9.10~~	~~5.94~~	~~6.19~~	~~3.75~~	~~-~~	~~-~~	~~5.24~~	~~5.21~~
~~r~~	~~0.46~~	~~-0.03~~	~~0.37~~	~~0.05~~	~~0.64~~	~~-~~	~~-~~	~~0.43~~	~~0.58~~
~~LE~~									
~~Bias~~	~~-0.33~~	~~-0.32~~	~~0.01~~	~~-0.37~~	~~-0.35~~	~~-0.28~~	~~0.25~~	~~0.26~~	~~0.09~~
~~RMSE~~	~~37.82~~	~~58.44~~	~~24.47~~	~~60.09~~	~~48.31~~	~~60.94~~	~~50.58~~	~~43.41~~	~~40.05~~
~~r~~	~~0.56~~	~~0.11~~	~~0.55~~	~~0.21~~	~~0.55~~	~~0.01~~	~~0.54~~	~~0.50~~	~~0.53~~
~~H~~									
~~Bias~~	~~-0.01~~	~~1.65~~	~~0.45~~	~~1.73~~	~~1.61~~	~~1.01~~	~~-0.38~~	~~0.50~~	~~0.22~~
~~RMSE~~	~~39.21~~	~~42.77~~	~~17.24~~	~~39.75~~	~~33.45~~	~~51.61~~	~~29.90~~	~~34.06~~	~~31.17~~
~~r~~	~~0.41~~	~~-0.04~~	~~0.76~~	~~-0.08~~	~~0.51~~	~~-0.10~~	~~0.45~~	~~0.18~~	~~0.31~~
~~Rn~~									
~~Bias~~	~~-0.12~~	~~-0.02~~	~~0.04~~	~~-0.11~~	~~-0.11~~	~~-0.04~~	~~0.04~~	~~-~~	~~-~~
~~RMSE~~	~~52.33~~	~~19.74~~	~~15.00~~	~~37.47~~	~~35.87~~	~~48.39~~	~~49.88~~	~~-~~	~~-~~
~~r~~	~~0.51~~	~~0.50~~	~~0.51~~	~~-0.22~~	~~-0.22~~	~~0.56~~	~~0.57~~	~~-~~	~~-~~

~~3.3~~4.3 Cover cropping and crop rotation~~scheme~~ scheme

The cover cropping scheme was tested for two fields of application: (1) simulation of a ~~second~~ cover crop as a second crop growth onset within a single year~~crop growth onset within one year and simulation of a cover crop~~, and (2) a more flexible crop rotation between different cash crops. In this step, simulations were run with the previously tested crop specific parameterizations for sugar beet, potatoes and winter wheat and results were again compared to a control simulation run, where a consecutive growth of spring wheat is simulated.

To test the first application of ~~CLM_WW_CC~~the cover cropping and crop rotation scheme, we simulated the cash crop and cover crop rotation cycle at DE-RuS from 2016 to 2017 (~~Figure~~Fig. ~~11~~7). A greening mix was planted as a cover crop in between the cash crop rotation of barley (simulated using the spring wheat CFT~~adopted from the spring wheat CFT~~) in 2016 and sugar beet in 2017. While only a consecutive growth cycle of spring wheat is simulated in the control run, the new routine was able to represent ~~While CLM_D simulated a perennial cycle of spring wheat, CLM_WW_CC was able to portray~~ the crop rotation from barley to sugar beet in the following year as well as ~~the coverage by a greening mix~~ a cover crop in between the cash crop cycles. Both, the simulation of a cover crop and the rotation of cash crops strongly improved the representation of LAI in ~~CLM_WW_CC~~ simulations with the new routine over multiple years, especially during winter months (~~Figure~~Fig. ~~10~~7, Fig. 8). While in ~~CLM_D~~control simulations, the model assumed bare field conditions with no plant growth (LAI of 0) and very low latent heat flux, ~~CLM_WW_CC~~the new routine simulated the ~~plantation~~ planting of a cover crop in fall of 2016, which leads to an increase in latent heat flux related to increased transpiration. Statistical evaluation of the simulated latent heat flux for the time window after harvest of the first cash crop from August 2016 to April 2017 shows that ~~CLM_WW_CC~~with the new routine, ~~reduced~~ the negative bias was reduced from 0.74 to 0.13 compared to ~~CLM_D~~control simulation results, resulting in an RMSE reduction by approximately 42 % (~~Figure~~Fig. 7~~10~~).



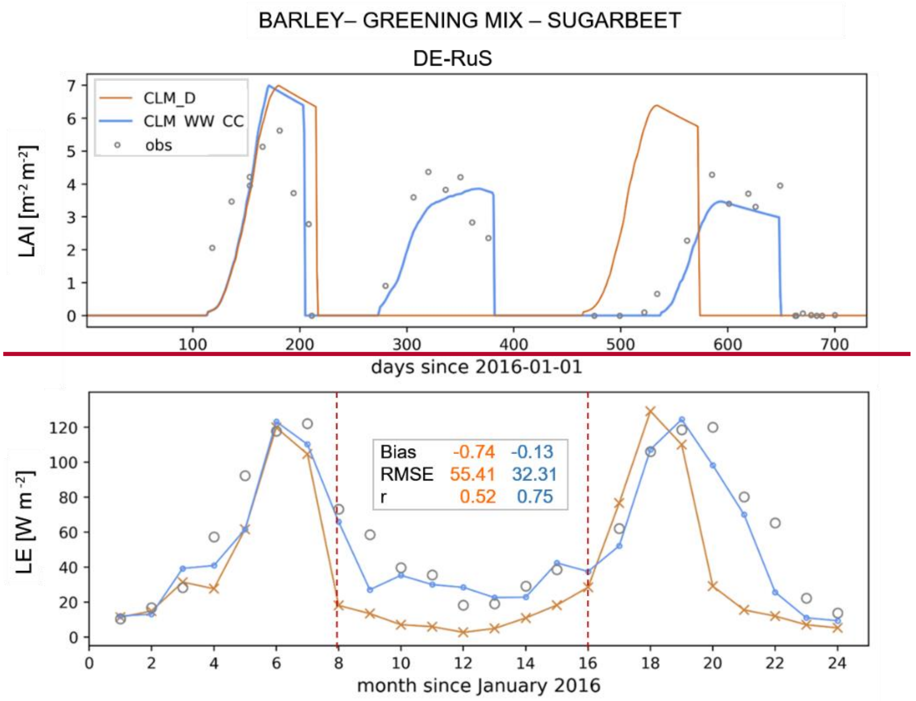
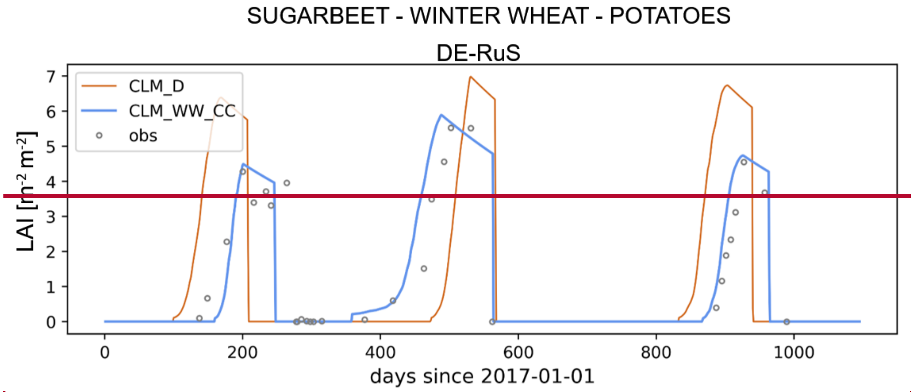


Figure 12: (Top) Simulated LAI for cover cropping at DE-RuS with a barley (2016), greening mix cover crop (2016/2017) and sugar beet (2017) using the new cover cropping subroutine (blue) in comparison to control simulation results with the default phenology algorithm of CLM5 (orange). rotation at DE-RuS and (Bottom) corresponding monthlyCorresponding monthly averaged simulation results for the latent heat flux with respective using the modified cover cropping subroutine CLM_WW_CC (blue) compared to the default phenology algorithm of CLM_D (orange). Corresponding bias, RMSE and r are given for the time window between the red dashed lines (, calculated using simulation output and observation data at daily time step). Available observation data areis plotted in grey.

For the second case (DE-RuS), which represents a higher flexibility towards cash crop rotation, we simulated the years of 2017 to 2019. Here, the crop rotation switched from sugar beet in 2017 to winter wheat in 2017/2018 to potatoes in 2019 (FigureFig. 118). While CLM_D was only capable of simulating a perennial spring wheat crop

In the control simulation, using the default CLM5 phenology algorithm, a consecutive cycle of spring wheat is simulated. The new routine, CLM_WW_CC was able to represent the rotation between different cash crops on the same field. This resulted in , which resulted in a much better correspondence of simulated LAI cycle and magnitudes with observations simulated LAI (by CLM_WW_CC) compared to control CLM_D simulations. Statistical analysis of the latent heat flux showed an improvement of the RMSE (calculated for daily simulation output and observation data over these three years) from 43.74 to 32.94 and the correlation coefficient from 0.40 to 0.63 with the new routine. The improvement in simulated energy fluxes for each CFT individually is in accordance with the results presented in the previous chapters (4.1 and 4.2). where results are analysed for each CFT respectively.



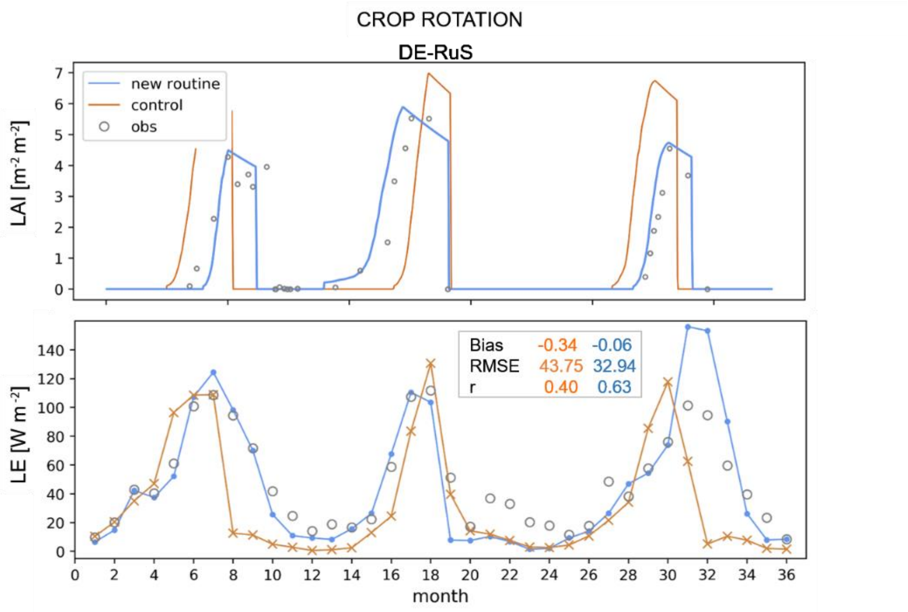


Figure 13: (Top) Simulated LAI for crop rotation from sugar beet (2017) to winter wheat (2017/2018) and to potatoes (2019) at DE-RuS using the new cover cropping subroutine (blue) in comparison to control simulation results with the default phenology algorithm of CLM5 (orange). (Bottom) Corresponding monthly averaged simulation results for the latent heat flux with respective bias, RMSE and r over the whole time interval (calculated using simulation output and observation data at daily time step). Available observation data are plotted in grey.

Simulated LAI for sugar beet (2017), winter wheat (2017/2018) and potatoes (2019) rotation at DE-RuS using the modified cover cropping subroutine CLM_WW_CC (blue) compared to simulation results for the same years with the default phenology algorithm of CLM_D (orange). Available observation data is plotted in grey.

45 Discussion

All three modifications that were implemented in this study helped to improve the representation of cropland sites in CLM5. Similar to the findings of Lu et al. (2017) for CLM4.5, the implementation of their winter wheat routine resulted in a significant improvement in representing the seasonal LAI variations and surface energy fluxes during winter wheat growth. Next to maize and rice, wheat is one of the most important international food crops and among the most important cash crops in Germany (22.8 million tons winter wheat yield in 2019 nation-wide (Statista, 2020)). In Germany and other western European countries, winter cereal varieties (e.g. winter rye, barley and wheat) are more abundant than summer cereals due to climatic conditions (Palosuo et al., 2011; Semenov and Shewry, 2011; Thaler et al., 2012). With an average annual winter wheat yield of around 20 Mt/a for Germany, an improvement of 87 % in simulated yield with CLM_WW compared to the default model (as observed at the DE-Rus site in 2018) could result in a difference of several tens of millions of tons in total predicted annual yield on a nation-wide scale.

Despite the general improvement of winter wheat growth and yield simulated with the modified CLM_WW, there is still potential in further increasing the flexibility towards simulating different crop varieties and management practices. Due to the phenology algorithm of CLM5, a low simulated LAI can indicate a lower grain yield due to low biomass growth. Accordingly, the higher simulated LAI for the DE-RuS site was associated with a slightly higher simulated grain yield for DE-RuS compared to BE-Lon. However, this relationship is not reflected in the observations, as the measured grain yield is lower for DE-RuS compared to BE-Lon, although the observed LAI is higher for DE-RuS (Figure 3, Table 3).

~~For example, the higher LAI captured at the DE-RuS site compared to BE-Lon was associated with a slightly higher simulated grain yield for DE-RuS, although recorded grain yield is lower compared to BE-LON (Table 4).~~ In CLM, there are several variables that influence the simulated crop yield, such as LAI cycle and peak, length of the leaf emergence phase, harvest date, and water availability from the soil. Except for soil moisture, these variables are strongly correlated to the GDD scheme which suggests that the simulated crop yield profoundly depends on the GDD. The high sensitivity of simulated yield in CLM towards GDD is not reflected in actual field observation, where crop yield depends on a multitude of factor, environmental conditions (weather, nutrient availability, atmospheric CO2) and management decisions. ~~This could be due to different management strategies such as fertilization application (timing, type and amount of fertilizer) or the usage of different winter wheat varieties that can show different responses to e.g. water or heat stress, frost and have different grain productivities (White and Wilson, 2006; Bergkamp et al., 2018; Ceglar et al., 2019). Here,~~ Underestimation of winter wheat yield at BE-Lon may be due to model deficiencies in representing the complex crop~~CLM5 is not flexible enough to represent the complex~~ management practices, such as ~~concerning~~ timing and type of fertilizer, ploughing crop varieties ~~or~~and the usage of different winter wheat varieties that can show different responses to ~~e.g.~~ water or heat stress, ~~,~~ frost and have different grain productivities (White and Wilson, 2006; Bergkamp et al., 2018; Ceglar et al., 2019)~~.~~. ~~In addition, CLM5 offers only one CFT for winter wheat representing all varieties.~~In order to include different varieties of any crop, the list of CTFs could be extended with suitable plant parameterizations. However, this information is not readily available, due to combination of measurement data scarcity and the complexity of the phenology algorithm and parameter scheme. The introduction of a phenology scheme based on plant physiological trait information in CLM could be a major improvement in this field (see Fisher et al., 2019), as plant trait information becomes more readily available (e.g. TRY Plant Trait Database, ~~(~~Kattge et al., 2011). ~~W~~Whether considering different varieties and cultivars of a crop ~~this~~ is ~~an~~ important ~~limitation~~ for regional or global scale simulations remains to be evaluated. In general, as already noted by Lu et al. (2017), a more process based vernalization and cold tolerance routine would be useful to make this subroutine more applicable to other winter crops like rapeseed.

The early leaf onset and harvest for winter wheat simulated by CLM observed overestimation of early LAI and underestimation of harvest date for winter wheat in CLM_WW (and(both with the new routine and parameter set and -the control runCLM_D) simulations could be met by adjusting the minimum date for planting within the CFT parameterization. This could be useful to easily improve the crop cycle representation in regional simulations, where planting patterns are similar for larger agricultural areas. However it would restrict the flexibility of the model to prognostically simulate planting dates.

In general, the simulated plant growth and resulting yield were highly sensitive to plant parameters that govern the growing degree calculation which in turn influence the phenological development and allocation of C and N. With only a limited number of CFTs in CLM, a discretization of plant parameters or varieties on a regional scale is not possible at this point. A potential solution, without introducing additional CFT´s, could be to account for key parameters for each CFT varying with climate and soil conditions for large scale simulations (e.g. by gridded parameter sets). Furthermore, there is a need to evaluate and further discretise plant hydraulic properties (at this point one set of hydraulic parameters is applied to all types of crops) (Verhoef and Egea, 2014; Kennedy et al., 2017; Kennedy et al., 2019). Within the crop module of CLM5, the carbon allocation of crops is limited by soil water available to the plant. Thus, both an improved soil hydrology Th and an improved representation of plant hydraulics is could play a major role in improving the quality of f the yield prediction by the model- (Bassu et al., 2014; Daniel Kennedy et al., 2019). These plant hydraulic properties could be estimated by inverse modelling or data assimilation (e.g. by assimilating measurement data like NEE, LAI, soil moisture and/or energy fluxes using an augmented state-vector approach). In addition, data assimilation of e.g. in situ or remotely sensed soil moisture data and/or LAI could play a major role in increasing the accuracy of regional yield predictions (e.g. Guérif and Duke, 2000; Launay and Guerif, 2005; de Wit and van Diepen, 2007; Fang et al., 2008; Vazifedoust et al., 2009; Huang et al., 2015; Jin et al., 2018).

The default CLM5 does not account for the influence of weeds or cover crops and/or its litter on the carbon balance. There is a tool available for CLM5 that enables the simulation of transient land use and land cover changes (LULCC) (Lawrence et al., 2018). It was designed to simulate and study the effects of changing distributions of natural and crop vegetation, e.g. land use change from forest to agricultural fields and also allows for changes in crop type between years -(Lawrence et al., 2018), rather than interbut does not account for intra-annual changes of agricultural management on crop vegetated areas that happen in double and triple cropping scenarios. However, While this tool is useful to study general land use changes by changing the land cover type of individual land units, we found it lacks flexibility in accounting for changes within land units of the same land cover and does not account for all 64 CFTs. that it is not applicable to regional scale simulations for all 78 available CFTs with customized changes in crop vegetation types. Furthermore, this tool changes the CFT of each column on the 1st of January every year according to prescribed values (customized). Thus, when using the CLM5 land-use change tool, for example to simulate the crop rotation from sugar beet in 2017 to winter wheat in 2017/2018 at DE-RuS, winter wheat would not be planted before fall of 20187 (rather than in the same year as sugar beet is harvested) resulting in a long period of fallow field when switching from summer to winter crop (FigureFig. 128). Here, the implementation of our cover cropping routine enabled a second onset of plant growth within a year (including the switch to another CFT). This resulted in a pronounced improvement in LAI curves and latent heat flux, especially during winter months, by simulating the growth of a cover crop. It also proved to be beneficial in representing realistic agricultural field conditions by allowing crop rotations with higher flexibility than the default model. This new routine can be used to study cover cropping scenarios in future large-scale simulations. The effect of a cover crop during winter months on all crop land units where cash crops are grown in summer could be tested. This could also be tested for specific cash crops only. In addition, it is possible to simulate cover crop plantations based on harvest date thresholds. A defined maximum harvest date for any specific cash crop could define whether a cover crop such as winter wheat would be planted or not. For example, for all sugar beet land units with harvest dates before a certain threshold (e.g. day 290 of any given year) winter wheat could be planted as a cover crop during winter. If this harvest threshold were not reached and the summer crop is harvested late in the year, no cover crop would be planted. Alternatively, these harvest thresholds could define the type of cover crop, e.g. early harvest - winter wheat, late harvest – simple greening mix, etc. Also, historical land use information could be used to simulate realistic cover cropping and crop rotation scenarios. The succession of different crops from historical data could also be used to model the succession of crops for the future. In order to study large scale effects of cover cropping and common crop rotations, the CLM5 model would greatly benefit from further crop specific parameter sets for cover crops such as mustard, and further important cash crops.

In their approach, Lombardozzi et al. (2018) studied the effects of idealized cover crop scenarios by simulating winter crops in all crop regions throughout North America. They found that the effects of cover crops on winter temperatures is strongly related to plant height and LAI and emphasized the importance of biogeophysical effects and varietal selection when evaluating the climate mitigation potential of cover cropping (Lombardozzi et al., 2018). With our new routine, it is now possible to evaluate the biogeophysical effects of cover crops over longer time scales and in combination with typical cash crop rotations throughout agricultural areas. Also the ecological potential of different cover crop varieties could be evaluated. We anticipate that this modification will allow a more realistic representation of seasonal LAI in ecosystems where cover cropping and crop rotations are common management practices. The application of this routine is also of interest for areas with several cash crop cycles within a year like multiple annual crop cycles in India and China (Biradar and Xiao, 2011; Li et al., 2014; Sharma et al., 2015).(Lombardozzi et al., 2018)(Lombardozzi et al., 2018)We anticipate that this modification will allow a more realistic representation of seasonal LAI in ecosystems and agricultural regions where cover cropping and crop rotations are common management practices. The application of this routine is also of interest for areas with several cash crop cycles within a year like multiple annual crop cycles in India and China (Biradar and Xiao, 2011; Li et al., 2014; Sharma et al., 2015). We see further development potential for this routine and corresponding data sets to account for typical crop rotations and cover cropping scenarios for regional scale simulations (e.g. EU regulations and goals on the adoption of cover crops for climate change mitigation (Smit et al., 2019))).

56 Conclusion

The default CLM5 was extended by adopting the winter wheat representation of Lu et al. (2017), by including crop specific parameterization for winter wheat, sugar beet and potatoes and by the addition of a cover cropping subroutine that allows several growth cycles within one year. The model modifications were tested for the respective crops at four TERENO and ICOS cropland sites in Germany and Belgium, Selhausen (DE-RuS), Merzenhausen (DE-RuM), Klingenberg (DE-Kli) and Lonzée (BE-Lon), for multiple years. The main results drawn from this study are as follows:

- The implementation of the winter wheat subroutines led to a significant simulation improvement in terms of energy fluxes, leaf area index, net ecosystem exchange and crop yield (reduction of underestimation from 80 – 90 % to 18 – 36 % at test site BE-Lon, good match for the test sites DE-RuS and DE-Kli in 2016 and slight overestimation at test site DE-Kli in 2011)
- The model performance was strongly improved with the ~~modified crop~~ crop specific parameter sets for sugar beet and potatoes: seasonal variations and magnitudes of energy fluxes and LAI were better reproduced with RMSE reduction during the crop cycle by up to 57 % for latent and 59 % for sensible heat flux at test site DE-RuS.
- In most cases the modification of CLM5 led to better reproduction of measured NEE at the test sites. However, the model showed a general weakness in reasonably simulating the NEE on agricultural fields, especially the peak value and post-harvest conditions.
- The implementation of our cover cropping routine enabled a second onset of plant growth within a year and thus was able to better capture realistic field conditions after harvest. Winter time RMSE for latent heat flux was reduced by 42 %. Also, a higher flexibility in terms of crop rotations is now possible with CLM5.

We anticipate that our implementation of the winter wheat representation and specified parameterization will markedly improve yield predictions at regional scale for regions with a high abundance of winter cereal varieties. The cover cropping routine offers an improved basis on which to study the effects of large scale cover cropping on energy fluxes, soil water storage, soil carbon and nitrogen pools, as well as to investigate the role of different cover crops as natural fertilizer in future studies with CLM5. A more realistic representation of post-harvest field conditions can play a crucial part in better representing the role of agriculture on~~for~~ regional and global energy and carbon fluxes and will be further developed and tested for regional scale simulations in future studies.

Despite our improvements, there is still a need to further develop certain functionalities and specific routines regarding the crop representation and land management in CLM5 in order to achieve better model performance for agricultural land. The applicability of the routines to large scale simulations would strongly benefit from additional crop specific parameterizations for important cash and cover crops. Also a better representation of ploughing and tillage needs be included in future model versions in order to better account for the effects of cover crops on the terrestrial carbon cycle and their biogeochemical benefits.

Further general e~~E~~xamples for improvements include: (1) an improved representation of plant and soil hydrology that may be highly beneficial for yield predictions, (2) a more detailed representation of agricultural management practices (e.g. tillage, C/N turnover, post-harvest surface conditions, fertilizer types and applications), (~~2~~3) tools to account for spatial variability in plant physiological parameters, and (~~3~~4) the discretization of plant hydraulic properties as opposed to using one parametrization for all crops.

~~6~~7 Appendix

Table A2: Sowing and harvest dates at the ICOS and TERENO cropland study sites

Site code	Site	Years	Crop	Sowing	Harvest/plowing
DE-RuS	Selhausen	2015-2016	Winter barley	29.09.2015	10.07.2016
		2016	~~Catch~~ Greening mix cover crop	22.08.2016	06.01.2017
		2017	Sugar beet	31.03.2017	05.10.2017
		2017-2018	Winter wheat	25.10.2017	16.07.2018

		2019	Potato	26.04.2019	03.10.2019
DE-RuM	Merzenhausen	2016	Potato	12.04.2016	24.08.2016
		2016-2017	Winter wheat	17.10.2016	22.07.2017
		2017-2018	Rapeseed	30.08.2017	16.07.2018
DE-Kli	Klingenberg	2003-2004	Winter barley	06.09.2003	31.07.2004
		2004-2005	Rapeseed	18.08.2004	02.08.2005
		2005-2006	Winter wheat	25.09.2005	06.09.2006
		2007	Corn	23.04.2007	02.10.2007
		2008-2009	Winter barley	25.04.2008	27.08.2008
				12.09.2008	22.07.2009
		2009-2010	Rapeseed	25.08.2009	24.08.2010
		2010-2011	Winter wheat	02.10.2010	22.08.2011
		2012	Corn	25.04.2012	18.09.2012
		2013-2014	Winter barley	17.04.2013	24.08.2013
				01.10.2013	20.07.2014
		2014-2015	Rapeseed	21.08.2014	08.08.2015
		2015-2016	Winter wheat	18.09.2015	24.08.2016
		2016-2017	Radish and Brassica ~~catch~~ cover crop	01.09.2016	15.03.2017
		2017-2018	Winter barley	02.04.2017	25.08.2017
		2016-2017	Radish and Brassica ~~catch~~ cover crop	13.09.2017	13.04.2018
		2018	Corn	02.05.2018	04.09.2018
		2019	Bean	23.03.2019	18.08.2019
BE-Lon	Lonzée	2006-2007	Winter wheat	13.10.2006	05.08.2007
		2008	Sugar beet	22.04.2008	04.11.2008
		2008-2009	Winter wheat	13.11.2008	07.08.2009
		2009	Mustard	01.09.2009	01.12.2009
		2010	Potato	25.04.2010	05.09.2010
		2010-2011	Winter wheat	14.10.2010	16.08.2011
		2012	Corn	14.05.2012	13.10.2012
		2012-2013	Winter wheat	25.10.2012	12.08.2013
		2013	Mustard	05.09.2013	15.11.2013
		2014	Potato	07.04.2014	22.08.2014
		2014-2015	Winter wheat	15.10.2014	02.08.2015
		2015	Mustard	26.08.2015	09.12.2015
		2016	Sugar beet	12.04.2016	27.10.2016
		2016-2017	Winter wheat	29.10.2016	30.07.2017
		2017	Mustard	07.09.2017	08.12.2017
		2018	Potato	23.04.2018	11.09.2018
		2018-2019	Winter wheat	10.10.2018	01.08.2019

Table A3: Default (*control~~d~~*) and ~~modified~~ new crop specific (*new~~m~~*) phenology and CN allocation parameters for the CFTs ~~temperate corn,~~ sugar beet and potatoes (~~both with default~~ control parameters are those for the ~~parameters for the~~ CFT spring wheat) and winter wheat.

CFT		**Sugar beet**		**Potatoes**		**Winter wheat**	
Parameter set		*control*	*new*	*control*	*new*	*control*	*new*
Variable	**Units**	***Phenology***					
min_NH_planting_date	MMDD	401	401	401	401	901	901
max_NH_planting_date	MMDD	615	530	615	530	1130	1130
planting_temp	K	280.15	280.15	280.15	277.15	1000	1000
min_planting_temp	K	272.15	272.15	272.15	272.15	283.15	283.15
gddmin	°days	50	60	50	60	50	100
mxmat	days	150	180	150	180	330	400
baset	°days	0	0	0	0	0	0
mxtmp	°C	26	30	26	30	26	26
hybgdd	-	1700	2000	1700	2000	1700	2000
lfemerg	%	0.05	0.05	0.05	0.05	0.03	0.03
grnfill	%	0.6	0.65	0.6	0.65	0.4	0.6
ztopmx	m	1.2	0.5	1.2	0.5	1.2	1.2
laimx	m^2/m^2	7	6	7	6	7	7
slatop	m^2/gC	0.035	0.02	0.035	0.02	0.035	0.028
Variable	**Units**	***CN ratios and allocation***					
leafcn	gC/gN	20	11	20	11	20	20
leafcn_min	gC/gN	15	8	15	8	15	15
leafcn_max	gC/gN	35	20	35	20	35	35
frootcn	gC/gN	42	42	42	42	42	43
graincn	gC/gN	50	50	50	50	50	15
flnr	fraction/gNm^{-2}	0.41	0.15	0.41	0.15	0.41	0.3

Table A4: Textural fractions (sand, silt and clay percentages) for the ICOS and TERENO cropland study sites averaged for the upper soil layers (up to 50 cm) with corresponding reference.

Site/ID	Sand [%]	Silt [%]	Clay [%]	Ref.
Selhausen/DE-RuS	16.4	63.4	14.9	~~(~~Brogi et al.~~,~~ (2019)
Merzenhausen/DE-RuM	16.4*	63.4*	14.9*	-
Klingenberg/DE-Kli	21.5	22.8	55.7	Grünwald (personal communication, 2020)
Lonzée/BE-Lon	5-10	68-77	18-22	~~(~~Moureaux et al.~~,~~ (2006)~~(Moureaux, 2006)~~

*adopted from the DE-RuS site

7.1 Winter cereal representation (extended)

The temperature at the crown of the plant (T_{crown}) is assumed to be slightly higher than the 2-m air temperature (T_{2m}) in winter when covered by snow, and the same as the 2-m air temperature without snow cover. Within CLM5, it is calculated separately for temperatures below and above the freezing temperature (T_{frz}):

$$T_{crown} = 2 + (T_{2m} - T_{frz}) * (0.4 + 0.0018 * (\min(D_{snow} * 100, 15) - 15)^2$$

for $T_{2m} < T_{frz}$ (A1)

$$T_{\text{crown}} = T_{2m} - T_{\text{frz}}$$

for $T_{2\text{m}} > T_{\text{frz}}$ (A2)

where T_{crown} [K] is the calculated crown temperature, $T_{2\text{m}}$ [K] is the 2-m air temperature, T_{frz} [K] is the freezing point and D_{snow} [m] is the snow height.

The temperature at which 50 % of the plant is damaged (LT_{50}) is calculated interactively at each time step ($\text{LT}_{50\text{t}}$) depending on the previous time step ($\text{LT}_{50\text{t-1}}$) and on several accumulative parameters. These parameters are the exposure to near-lethal temperatures (rate_s), the stress due to respiration under snow (rate_r), the cold hardening or low temperature acclimation (contribution of hardening – rate_h) and the loss of hardening due to the exposure to a period of higher temperatures (dehardening – rate_d) that are each functions of the crown temperature (Lu et al., 2017 and references therein):

$$\text{LT}_{50\text{t}} = \text{LT}_{50\text{t}-1} - \text{rate}_h + \text{rate}_d + \text{rate}_s + \text{rate}_r \qquad \text{(A3)}$$

The exposure to near-lethal temperatures is based on the winter survival model after (Fowler et al., 1999) and is calculated as follows:

$$\text{rate}_s = \frac{\text{LT}_{50\text{t}-1} - T_{\text{crown}}}{e^{-1.9(\text{LT}_{50\text{t}-1} - T_{\text{crown}}) - 3.74}} \qquad \text{(A4)}$$

The stress due to respiration under snow is calculated as a function of snow depth (dsnow) that ranges from 0 to 1 for snow cover up to 12.5 cm (equal to 1 for all snow depth higher than 12.5), and a specific respiration factor (RE):

$$\text{rate}_r = R \text{ x RE x } f(\text{dsnow})$$

$$R = 0.54 \; f(\text{dsnow}) = \min(\text{dsnow}, 12.5)/12.5$$

$$\text{RE} = \frac{e^{0.84 + 0.051\,T_{\text{crown}} - 2}}{1.85} \qquad \text{(A5)}$$

The contribution of hardening and dehardening are calculated within certain temperature ranges as follows:

For $T_{\text{crown}} < 10$°C

$$\text{rate}_h = 0.0093(10 - \max(T_{\text{crown}}, 0))(\text{LT}_{50\text{t}-1} - \text{LT}_{50\text{c}}) \qquad \text{(A6)}$$

For $T_{\text{crown}} \geq 10$°C when vf < 1 (not fully vernalized), and $T_{\text{crown}} \geq -4$°C when vf =1 (fully vernalized)

$$\text{rate}_d = 2.7 \text{ x } 10^{-5}(\text{LT}_{50\text{i}} - \text{LT}_{50\text{t}-1})(T_{\text{crown}} + 4)^3 \qquad \text{(A7)}$$

where $\text{LT}_{50\text{c}}$ is the maximum frost tolerance of -23 °C and $\text{LT}_{50\text{i}}$ represents the LT_{50} for an unacclimated plant ($\text{LT}_{50\text{i}} = -0.6+0.142\ \text{LT}_{50\text{c}}$).

The survival rate (f_{surv}) is then calculated as a function of LT_{50} and the crown temperature. The probability of survival is a function of T_{crown} in time (t). It increases once T_{crown} is higher than LT_{50} or decreases when it is lower (Vico et al., 2014):

$$f_{\text{surv}}(T_{\text{crown}}, t) = 2^{-\frac{T_{\text{crown}}}{LT_{50}}^{\alpha_{\text{surv}}}} \qquad \text{(A8)}$$

where α_{surv} is a shape parameter of 4.

The winter killing degree day (WDD) is calculated as a function of crown temperature and survival probability, where the maximum function limits the integration to the potentially damaging periods, when the air temperature (T) is lower than the base temperature (T_{base}) of 0°C (Vico et al., 2014):

$$WDD = \int_{\text{winter}} max[(T_{\text{base}} - T_{\text{crown}}), 0]\,[1 - f_{\text{surv}}(T_{\text{crown}}, t)]dt \qquad \text{(A9)}$$

Lower LT_{50} indicate a higher frost tolerance and would result in higher survival rates, smaller WDD and less cold damage to the plant. Thus, when the survival probability and crown temperature are low, the WDD will be high (Vico et al., 2014).

The survival probability and the WDD are then used to estimate instant and accumulated frost damage to the crop during the leaf emergence phase (Lu et al., 2017). Instant frost damage is assumed to happen at the beginning of the growing season when the plants are not fully vernalized (vf < 0.9) when the growth of leaves (especially new leaves or small seedlings) due to an exposure to low temperatures. It is simulated by reducing the leaf carbon at low survival probabilities (whenever f_{surv} is below 1). The leaf carbon is reduced by an amount of 5 gC m^{-2} scaled by a factor of 1- f_{surv} that is moved to the carbon litter pool, up to a minimum value of 10 gC m^{-2} leaf carbon:

$$\text{leafc}_t = \text{leafc}_{t-1} - \text{leafc}_{\text{damage}}(1 - f_{\text{surv}})$$

for vf < 0.9, WDD > 0, f_{surv} < 1, and leafc_t > 10 (A10)

where leafc_t is the simulated leaf carbon of the current time step, leafc_{t-1} is the leaf carbon of the previous step and $\text{leafc}_{\text{damage}}$ is equivalent to 5 gC m^{-2}.

When the plant is close to vernalization towards the end of the leaf emergence phase, it is not as susceptible to suffer from instantaneous frost damage as in the beginning of this phase. Still, an extended period of freezing temperatures can potentially induce damage to the plant (Lu et al., 2017). This accumulated frost damage is simulated based on the accumulated WDD and average survival probability. When the accumulated WDD reaches a value higher than 1° days, the leaf carbon from the previous time step (leafc_{t-1}), scaled by the average f_{surv}, is moved to the soil carbon litter pool:

$$\text{leafc}_t = \text{leafc}_{t-1}(1 - \text{average } f_{\text{surv}})$$

for vf ≥ 0.9 and WDD > 1 (A11)

Once this has occurred, the accumulated WDD is reset to 0 and the tracking of the average f_{surv} is restated. Corresponding to the leaf carbon reduction, the leaf nitrogen is reduced from the leaf nitrogen pool to the soil nitrogen litter pool scaled with the parameterized leaf C/N ratio for winter wheat of 20.

Code availability. The modified model version CLM_WW_CC is freely available via Zenodo, doi:10.5281/zenodo.3978092.~~GitHub: https://github.com/HPSCTerrSys/CTSM/tree/release-clm5.0-boas_ww_cc.~~

Data availability. For the TERENO sites Selhausen (TERENO ID: SE_EC_001 and SE_BK_001) and Merzenhausen (TERENO ID: ME_EC_001, ME_BCK_001), all EC and meteorological data ~~is~~ are freely available via the TERENO data portal TEODOOR (http://teodoor.icg.kfa-juelich.de/): Selhausen – ID SE_EC_001 doi:20.500.11952/TERENO/00000004; Selhausen – ID SE_BDK_001 doi:20.500.11952/TERENO/00000068; Merzenhausen – ID ME_EC_001 doi:20.500.11952/TERENO/00000434; Merzenhausen – ID ME_BCK_001 doi: 20.500.11952/TERENO/00000166. EC data for the ICOS study sites Lonzée (ICOS ID: BE-Lon) and Selhausen (ICOS ID: DE-RuS) is available via the ICOS data portal (https://www.icos-cp.eu/). Additional data on vegetation and management practices (e.g. LAI, NDVI, canopy heights etc.) were kindly provided by the respective site operators.

Competing interests. The authors declare that they have no conflict of interest.

Author contribution.T. B. developed the modified model code, designed, performed and analysed the simulation experiments and prepared the manuscript with contributions from all co-authors. H.B., H.J.H.F., D.R., A.W. and H.V. supervised the research, co-designed the experiments and ~~reviewed~~ contributed to the manuscript. M. S., B. G. and B. H. performed pre-processing (e.g. quality control, gap-filling) of the respective site data.

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