Dear Editor and Referees,

Thank you for the thorough evaluation of our manuscript and the very helpful and detailed feedback. This is much appreciated. We were able to address all of the reviewers' points, which improved the model as well as its presentation in the paper.
In this letter we list the referees' comments, each point followed by our responses, and the changes in the manuscript, as a follow up to interactive comment on 06-02-2019.

The responses and subsequent modifications to the model and manuscript have been derived in consultation with all co-authors.

The updated source code of the modified model is available at https://cloud.pik-potsdam.de/index.php/s/zAbLbXavcIVY6Xn [password: lpjml5080] and will be archived and published (under the AGPLv3 license) upon acceptance of the paper.

Best regards,
Tobias Herzfeld and Femke Lutz

Referee #RC1

The authors have developed a module in LPJmL, which simulates some biophysical effects of tillage on carbon, water and N_2O fluxes. The work is very relevant to GMD and the wider scientific community, enabling a wide range of applied studies. However, I believe the manuscript should not be published. The main reason is that in the model development for water fluxes important processes were either neglected or misrepresented to the point that effects might be not only uncertain, but possibly wrong. In the following, I will explain this in more detail.

Referee comment 1: In the proposed model, soil moisture changes are affected by an increase in bulk density in no-tillage (NT), reducing infiltration rates. The problem is, that while this is fine in theory, hydraulic conductivity based on bulk density is not related to runoff production in any meaningful way. The evidence is that runoff generation is hardly affected at the local scale, and decreases with increasing field scale, sometimes dramatically (Shipitalo et al 2000). Reviews show that the effect is very variable, but on average, on plot or field scale, NT reduces runoff (Leys et al 2010, Armand, 2009), while the proposed model suggests an increase in runoff. The authors acknowledge that processes such as preventing crusting by residues and preferential flow might increase infiltration, but they do not implement these important processes, and as a consequence they get the effect wrong.

Answer 1: *Thank you for pointing to this. Indeed, we had missed to address the positive effect of NT on infiltration as well as to clearly communicate our results and the underlying mechanisms. As suggested by the reviewer and literature, infiltration is enhanced under no-tillage as soil crusting is reduced and preferential pathways are affected. As a result, surface runoff decreases on average. We now further extended the model to include improved infiltration rates under residue cover. To do this, we follow the approach by Jägermeyr et al. (2016), equation 1, which has been developed for implementing in situ water harvesting, e.g. by mulching, in LPJmL and is suitable for global-scale model applications. Given that a direct modeling of soil crusts depends on a lot of detailed information that is not available at the global scale (e.g. precipitation intensity, which is e.g. needed for the Green-Ampt infiltration routine) and modeling attempts are often found to be unsatisfactory even at field scale (Nciizah and Wakindiki, 2015), we believe that the simple approach described by Jägermeyr et al. (2016) is more suitable and also allows for more systematically addressing model uncertainties. In the now revised tillage implementation, the infiltration rate is dependent on the residue cover, so that infiltration is increased with increasing residue cover. With this revised implementation of tillage, we find a substantial reduction in surface runoff (-57.6%) under NT_R compared to T_R.*
We note that this modification of infiltration has moderate, but generally positive effects on the simulation of the other stocks and fluxes and simulation results are now closer to the reported literature values (e.g. CO_2 and N_2O emissions and crop yields).
We also revised the manuscript with respect to clarity, as we had only reported total runoff (surface runoff + lateral runoff + seepage) whereas only surface runoff is reported in the suggested literature. We now include model outputs on surface runoff for better comparability to literature values.

Changes in manuscript 1: We now included the infiltration approach by Jägermeyer et al. (2016) in LPJmL5-tillage and included a new chapter on soil infiltration (chapter 3.3.2), explaining the approach in detail, starting from line 244. For the evaluation of water fluxes in chapter 5.4, we now only analyze surface runoff, which is substantially reduced under surface litter for NT_R vs. T_R, see line 566, also Appendix 4.

Referee comment 2: Figure 1 suggests a link between residue cover and infiltration, which they do not model. Instead they model residue interception, which they term infiltration because they treat the residue layer as a soil layer. This is confusing, because interception is a very different process from infiltration. Residues are labelled as 'layer' into which infiltration can happen. This is contrary to the common definition of infiltration, which is water flux across the soil surface. This is not merely a semantic problem. Interception effects alone reduces infiltration into the actual soil, while their model scheme suggests an increase in infiltration. Residues do have a positive effect on infiltration, of course, through reducing sealing / crusting, but they do not model this.

Answer 2: *We agree that the term infiltration was not used correctly here. In the manuscript, the term is now changed to residue interception as the water is infiltrating into the first soil layer after passing through the residues (if present) and part of the rainfall will thus be intercepted. The residue cover is not treated as a soil layer. We corrected and clarified this in the manuscript, including Fig. 1. For the comment related to the positive effect of residues on infiltration, we would like to refer to our response on the first issue raised by reviewer 1. Within the model, surface litter now does not only intercept part of the rainfall but also enhances infiltration. These changes to the model implementation are now reflected in the updated version of Fig. 1.*

Changes in manuscript 2: We have renamed chapter 3.3.1, which is now called "litter interception", see line 219. The model now also accounts for increased infiltration under surface litter (chapter 3.3.2, line 244 ff). We have also changed all wording in the entire manuscript from "residue layer" to "surface litter" and have updated Fig. 1 accordingly.

Referee comment 3: CO_2 emissions decrease in the short term with NT, and increase in the long-term. Unless there is more C-input with NT, this is not a reasonable outcome, and also contrary to literature, as the authors suggest themselves. If there is more C-input for NT, the authors need to be clear about it. If there is more C-input (from increased NPP), that would also be inconsistent with meta-analyses of yields, which generally find no significant difference with tillage.

Answer 3: *CO_2 emissions are variable in space and time and indeed subject to different drivers, which are covered by our model. For the majority of cropland areas (median reported in Table 4 of the manuscript), CO_2 emissions initially decrease after introducing no tillage (NT_R vs. T_R), which is consistent with literature and theory, as pointed out by the reviewer. In table 4 of the original submission, we had accidentally reported the values after 10 years not after 2 (year 1-3 average). There are two explanations for CO_2 to increase in the long term under no-till: 1) there is more C input for NT from increased NPP or 2) the decomposition rate is higher under NT over time, due to changes in e.g. soil moisture or temperature. When looking at the initial response, CO_2 emissions indeed decrease almost everywhere. After 10 years, CO_2 emissions continue to decrease in most humid regions, whereas they start increasing in drier regions. These are also the regions where we observe a positive effect of reduced evaporation and increased infiltration on plant growth, i.e. in these regions the C-input is substantially increased under NT-R compared to T-R. The relative differences of residence time of soil carbon for NT-R compared to T-R are relatively small (+1,5% after 10 years), but show similar patterns, i.e. the residence time decreases in drier areas but increases in more humid areas. As such, both mechanisms that affect CO_2 emissions are reinforcing each other in many regions. This is in agreement with the meta-analyses conducted by Pittelkow et al. (2015), who report yields (and thus general productivity and thus C input) often to be equal or higher in NT than in CT in dry climates after 5-10 years. Their results show that in general, NT performs best relative to CT under water-limited conditions, due to enhanced plant water availability when residues are retained. We modified the text to clarify the effects of NT on the processes that affect CO_2 emissions and to describe in detail how different responses in CO_2 emissions in space and time can be explained. We added a new chapter on evaluating crop productivity. In this chapter, the increase in productivity under NT_R is discussed for rain-fed maize and wheat. In general, increase in productivity can be observed in arid areas and therefore also C input. The increase in productivity diminishes when the areas become less arid, which is in agreement with literature studies (see chapter 5.2). We have updated and revised the chapter 5.3 (previously chapter 5.2) and now better explain the underlying mechanism leading to a CO_2 increase after ten* *years under NT_R vs. T_R. We also included a new map for relative changes for CO2, C-input, turnover time and topsoil and litter C change after ten years (Fig. 3) and after two years (Appendix 3). For example, we see that turnover times are substantially increased under NT_R after two years while they decrease after ten years due to changes in moisture regime and C-input.*

Changes in manuscript 3: The new chapter on evaluating the productivity (chapter 5.2) can be found from line 478 ff. In general, increases in productivity can be observed in arid areas and therefore also C input (chapter 5.3). We added Fig. 3 showing relative C dynamics for NT_R vs. T_R after ten years for CO2, relative C input, change in turnover time and topsoil and litter change.

Referee comment 4: For N_2O, the authors acknowledge the uncertainty of the equations they use. However, the problem is compounded by the uncertainty of (and possibly wrong) effects calculated for soil moisture.

Answer 4: *Simulating N_2O emissions is very challenging, as there is a high spatial and temporal variability in this flux. Moreover, it is very sensitive to soil moisture and it is therefore indeed important to correctly simulate this. The modification of the infiltration function as described in the response to account for residue effects on crusting (see the response on comment 1) has an effect on soil moisture, and therefore on N_2O emissions; the N_2O emissions increased from +7.5% to +18.3% under NT which is closer to the value reported by Mei et al. (2018), who reports an increase of 36.1%. When looking at climate regions, we find that the simulation of N_2O emissions are closer to the observed value of Mei et al. (2018) for all regions, except for the cool- and humid zones, where Mei et al. (2018) report a small decrease, whereas the new infiltration scheme further increases N_2O emission in our model. A comprehensive analysis of the uncertainty of simulating N_2O emission by the model lies beyond the scope of this study but will be investigated in a follow-up study, by conducting e.g. pixel analysis / sensitivity studies. The mechanisms leading to the increased N_2O emissions under NT as well as the spatial patterns and uncertainty are now better explained in the revised manuscript.*

Changes in Manuscript (4): We extended the chapter 5.5 on N_2O emissions. There we discuss that the increase in N_2O emissions is mostly resulting from denitrification. We added a discussion in relation to changes in soil moisture, which mostly determines N_2O emissions from denitrification. For this we added also a Fig. 5 with global maps, showing relative changes of NT_R vs. T_R for denitrification, nitrification, soil water and total soil NO_3. In general, uncertainties do exist for the simulation of soil moisture at various scales (see e.g. Seneviratne et al., 2010). These uncertainties are now discussed in lines 654-665.

Referee comment 5: In summary, in the current form, some of the process representations are insufficient leading to wrong or very uncertain effects. The authors do mention some of these processes in the discussion, but there is no justification that despite these omissions we can trust the modelled effects. There are some more general remarks about the manuscript.

Answer 5: *We believe that, with the modified infiltration function (see response to the first comment), the representation of processes is improved. In the manuscript, we now more explicitly point out uncertainties and where correct responses to tillage practices are found. We are convinced that the now updated version of the model is a substantial improvement compared to previous model version of LPJmL (where tillage was not addressed at all), which is our main aim in this model description paper. We also think that a detailed representation of tillage effects in a global crop, hydrology and dynamic vegetation model is a general advancement of modeling capacities. We can demonstrate that many modeled effects of tillage are within expected ranges and we explicitly address uncertainties and lack of agreement with reference data in the revised manuscript. We think that the ability of the model to reproduce diverse responses in space and time are an asset of the model, reflecting the diversity in outcomes also in experimental data and the importance of climatic, soil and management conditions. We have now included the modified infiltration function into the model and only explain model behavior with processes which are actually modeled.*

Changes in manuscript 5: We have updated the chapter 5.3, 5.4, 5.5 and also the general discussion, chapter 5.6, on model uncertainties. Despite these uncertainties, we still find reasonable and correct response of our model in regard to soil and litter C stocks, productivity feedbacks and water fluxes, which are now better explained and described in the revised manuscript. For water fluxes, we added a new Fig. 4 comparing modeled results from surface cover on evaporation and surface runoff to literature values from Ranaivoson et al. (2017).

Referee comment 6: Cursory reading of important literature: this is evident in the two first points made above. Also, for water fluxes, only the aspect of reduced soil evaporation is compared to a single study. Also they claim that there are no models for crusting effects and no other PTFs with SOC, which is not true (Zhang et al. 1995, Risse et al 1995, Balland et al 2008). For SOC change very few of the more recent SOC meta-analyses were referenced. I suggest to use the citations of Ogle et al 2005 as starting point, see also Haddaway et al 2017.

Answer 6: *We agree that the existing literature was not sufficiently reflected in the original submission of the manuscript and we expanded that in the revised version. Soil crust formation and adjustments of K due to crusting as proposed by Risse et al. (1995) and Zhang et al. (1995) are calculated from cumulative kinetic rainfall energy, which is currently not available at the global scale. Please also see refer to issues 1 and 2. We have added two more references to evaluate the effects of water fluxes (Ranaivoson et al., 2017, Scopel et al., 2004) and removed the reference for Steiner (1989), because we found that he only analyzed stage one evaporation (equal to potential evaporation), which is not a fair comparison. We now compare our results to a meta-analysis from Ranaivoson et al., 2017 for different soil cover values, which are visualized in Fig. 4. We updated the evaluation and discussion part on this in chapter 5.4. We now also better justify our choice for using the PTF by Saxton and Rawls (2006) in chapter 3.5.1 and in 5.1.*

Changes in manuscript 6: The changes can be found in chapter 3.5.1, from line 306ff for the description of the pedotransfer function. We also added references to reviews for PTFs application and comparison, see line 312. We updated chapter 5.4 for the evaluation of water fluxes, line 565ff.

Referee comment 7: The manuscript is misleading at parts. The start of section 2 suggests model development which was not implemented in the way described. Please be very clear in all parts of the manuscript what was implemented and what not. Also some parts of the discussion gloss over the problems with the partiality of model development, and the problems with the literature comparisons they make (please refer to the specific comments). Moreover the section on tillage effects on bulk density was nearly literally taken over from APEX/EPIC model, this should be acknowledged more clearly (not just with a reference to the model documentation).

Answer 7: *Thank you for the specific comments. We addressed all of them in the revisions and update the manuscript in the parts that are misleading. We see that clarification was especially needed in regard to the water fluxes, as already discussed in comment 1 and 2 as well as in the description of model implementation and model evaluation against reference data. We have revised and restructured chapter 2, so the processes are now better explained and we now only focus on processes, which have been implemented into the model. We also revised chapter 3.5.2, which is now merged from the old chapters 3.5.2 and 3.5.3 to better acknowledge the APEX/EPIC model. We now also refer directly to the first publication of the EPIC model by Williams et al. (1983) in chapter 3.5.2. Parts of the discussion have been revised to better explain the processes involved, which lead to our results.*

Changes in manuscript: Changes to manuscript can be found in chapter 3.5.2, from line 356 onwards.

Referee comment 8: The authors should reformulate the last paragraph of the introduction as (a set of) objectives. Is the objective just to describe the new module? I think the evaluation of the module is an objective, too.

Answer 8: *We now added the objectives to the introduction. The objectives of this study are to 1) describe the new tillage module in LPJmL in full detail and 2) evaluate the new tillage module against literature values reported in meta-analyses using a set of stylized management scenarios.*

Changes in manuscript 6: We added the objectives of this paper in the introduction, chapter 1, line 62-65.

Referee comment 9: Although not specified, the objective of the paper is to describe a new tillage module in LPJmL. They state that this has been done so in other models, but (presumably) to an unsatisfying level. The authors need to be very specific about the state-of-the-art tillage modelling in global dynamic vegetation models / gridded crop growth models, and how (if at all) they improve on existing formulations.

Answer 9: *One of the objectives of the paper is indeed to describe a new tillage module in LPJmL. The objective is not to propose a new approach to represent tillage in crop models, but rather to describe the extension of*

LPJmL so that management effects on biophysical processes and biogeochemistry can be better represented in LPJmL. The implementation is guided by existing modeling approaches and we have extended LPJmL in a way that is more process-based than other approaches (e.g. Pugh et al., 2015), but still suitable for global-scale applications, in which calibration is strongly impeded by the lack of reference data and several driving data are not available (e.g. rainfall intensity, management practices). The choice for representing tillage at a process level rather than simple scaling factors introduces additional uncertainty, which we acknowledge and discuss. However, it also allows for improved understanding, e.g. by comparing different soil properties to reference data, and for accounting for the spatial heterogeneity in soil, climate and management conditions. We do not intend to predict the effects of tillage with high certainty, which is not possible at the global scale with the associated lack of detailed data. Instead, the main purpose is to enhance the understanding of the complexity of tillage effects at the global scale and to upscale findings from field experiments. This now better better described and discussed this in the revised manuscript. We also expanded the introduction by discussing the state-of-art of tillage modelling in DGVMs and crop growth models.

Changes in Manuscript 9: We have extended the introduction, chapter 1, to clarify the objectives of the study (line 62-65), and the state-of-art of tillage modeling in global ecosystem models (line 53-61).

Referee comment 10: The methodological explanation on the comparisons between NT and T results (4.2) and the subsequent comparisons can be improved, currently this requires 2 or 3 re-readings.

Answer 10: *Thank you. We have rephrased section 4.2 (line 416 ff) for clarity.*

Changes in manuscript 10: We revised chapter 4.2 for clarifying the experimental set-up, from line 416 onwards.

Referee comment 11: Specific comments: See annotated pdf in supplement to comments.
Answer 11: *Thank you for the specific comments. We revised the manuscript accordingly.*

Changes in manuscript 11:
We rephrased sentences and/or added information for clarity and added new references where it was requested and also worked on the following comments that were in the supplementary material:

- We revised the introduction an added more references in line 32.
- We explain in more detail explain why we chose the processes implemented into the model in chapter 2, line 77-79; 112-118.
- We corrected all the equations in order to 1) use the same symbols and acronyms as in prior LPJmL publications, and 2) added equations related to N-pools (e.g. chapter 3.2 line 157-163; 207-208).
- We moved the explanation of soil texture used in LPJmL from chapter 3.5.1 to chapter 4.1, line 409.
- Variations in C stocks and the CO_2 response are now better explained in chapter 5.3. We have revised all chapters (5.1-5.6) for evaluation and discussion and added a new chapter for productivity (5.2).
- We now also account for an increased infiltration under surface litter and discuss the modeled results in chapter 5.4 (lines 565ff).

Referee #RC2

Referee comment 12: General comments: The work presented in this paper putting forward a 'tillage' module for LPJmL model version 5.0 is the perfect fit for GMD as a journal enabling outreach to a wider community of ecosystem, earth system and atmospheric modelers. It is definitely a crucial addition in the suit of tools that enable evaluation of soil N and C dynamics resulting in CO_2 and N_2O emissions and how they are impacted by agricultural management practices like, tillage in conjunction with other practices like use of residue cover. However, after going through the GMD Discussions draft submitted, it seems to require some major revisions in terms to addressing the scientific assumptions to modeling approach used in this proposed module, before it can go ahead for final publication.

Answer 12: *Thank you for the positive general assessment. We modified the manuscript for better clarity in scientific assumptions and in the overall presentation of results.*

Changes in manuscript 12: We have now modified almost all parts of the manuscript and also included a new infiltration approach under surface litter, which generally improves results, see chapter 3.3.2, line 244 onwards. We also updated the maps and discussion the general presentation of our results.

Referee comment 13: There are some structural discrepancies in how some processes that are not actually modeled as listed in Fig 1 are still listed in the text as explanation for model performance.

Answer 13: *Thank you for your comment. We now strictly focus only on processes which have been implemented into the model and clarified the specific sections. We now further included a mechanism of improved infiltration in relation to residue cover. In the revised manuscript we are now more specific on the processes which are actually modelled and updated Fig. 1 in this regard. We have revised and restructured chapter 2 for clarity and to better explain the processes which were included. We also updated Fig. 1 in this regard. The text in the result and discussion section is now revised to specify when we are discussing about processes that we included or not.*

Changes in manuscript 13: The changes to the manuscript can be found in chapter 2, from line 73 onwards, see also the updated Fig. 1.

Referee comment 14: More discussion on soil Nitrogen pools and their dynamics with different management strategies along with soil Carbon pools is needed both in terms of explaining the N_2O emissions better, as well as adding differentiation between C and N parts of SOM in equations by incorporating C:N ratios.

Answer 14: *Thank you for this comment. We realize that we have not sufficiently described which functionality refers to carbon and/or nitrogen pools and fluxes and will update the equations and the description accordingly for better clarity. We now more clearly distinguish C and N pools and added equations for N related processes where relevant. We also included equations for* N_2O *related processes.*

Changes in Manuscript (14): The distinguished pools of C and N and corresponding equations for N related processes can be found in chapter 3.2, line 157-163. The equations for N_2O related processes can also be found in chapter 3.2, line 207 and 208.

Referee comment 15: It would be helpful to list in a tabular form or in form of figures, as to how the proposed tillage module improves upon the already available modeling approaches for effects of Tillage on SOM dynamics, soil properties, crop yield, CO2 and N_2O emissions.

Answer 15: *We updated this section and discuss in more detail on how our implementation is different from already existing model approaches. The main objective of this paper is to present the updated version of the process based LPJmL5 model, which has now been improved by including tillage management and a detailed interaction of processes of residues effecting soil water content. We now also explain this in more depth in the text including the difference between our approach and that of other global models (see also answer 9). A comparison of how tillage is modeled in other biophysical models can also be found in Lutz et al. (2019), which we refer to in the revised manuscript. We have extended the introduction, chapter 1, to point out the state of knowledge of tillage modules in other models*

Changes in manuscript 15: The extensions to the introduction, chapter 1, can be found in line 53-61). In order to avoid redundancy, we did not include a tabular form of modeling approaches in the manuscript, as this is already available in other manuscripts (e.g. Lutz et al., 2019; Maharjan et al., 2018), see reference in line 53.

Referee comment 16: Effects of tillage on Bulk density is adapted from APEX v0806 model (http://epicapex.tamu.edu/files/2014/10/APEX0806-theoretical-documentation.pdf), however it seems it has been assumed that Bulk density after tillage = Bulk density after soil completely settles, which is not necessarily accurate all the time after Tillage. Moreover, this assumption is really not highlighted in the text.

Answer 16: *We indeed assume that the bulk density after tillage can reconsolidate over time to its original bulk density prior to tillage. The rate of reconsolidation depends on the infiltration rate and sand content of the soil. We are aware of the problem of the so called fluffy soil syndrome, which is the results of tillage without a wetting cycle under dry condition* (Daigh and DeJong-Hughes, 2017)*. However, this topic is not yet very well* *researched. Since in our model soil consolidation is dependent on water infiltration, in dry regions the soil possibly does not consolidate back to its original state in all cases. This effect can also vary from year to year. Any negative implications from this effect are not yet part this tillage model implementation. We have revised the manuscript to more clearly describe the dynamics of changes in bulk density after tillage and the gradual reconsolidation over time. We now changed the model implementation to also account for previous bulk density, if the soil has not completely settled.*

Changes in manuscript 16: The effect is now in more detail explained in chapter 3.5.2, equation (28), line 368. We do not account for any negative implications from the so called fluffy soil syndrome, which is now referred to in the text, chapter 3.5.2, line 392-394.

Referee comment 17: There can be huge uncertainty in terms of how CO_2 and N_2O emissions are effected by additional management practices adopted with Tillage or No tillage, under short or long term analysis for different crops and climate with varied soil properties. This needs to be explained more as to how such kind of uncertain behavior can be explained by proposed LPJmL-Tillage version 5.0 currently and what aspects need more work in the future.

Answer 17: *Indeed, different environmental conditions (soils and climate) and management practices other than tillage strongly determine the effects of tillage on soil properties and thus also CO_2 and N_2O emissions. The process-based representation of tillage effects in the LPJmL model allows for representing the complex and diverse effects of tillage across environmental and management gradients, which are reflected in the broad variability in N_2O and CO_2 responses under different tillage experiments. Indeed, we also find that the modeled impacts of tillage are very diverse in space as a result of different farming conditions (soil, climate, management) and feedback mechanisms, such as improved productivity in dry areas if residue cover increases plant-available water. It is indeed important to understand which processes lead to uncertainties in those fluxes. Therefore, we evaluated model performances by using results of meta-analyses. Even though there are not enough reference data to verify the simulated spatial patterns in e.g. CO_2 and N_2O emissions, we think that the ability of the model to reproduce a broad diversity of tillage effects in response to environmental conditions is an asset of the model that can be employed to explicitly study soil management and associated biogeochemical effects, including uncertainty. We extended the general discussion on these aspects and point out future research needs to better address those uncertainties.*

Changes in manuscript 17: We restricted our analysis to the availability of observations from meta-analyses. We extended the general discussion on sources for uncertainty, see line 681 onwards. We also now included in the discussion what aspects need to be worked on in the future, see lines 704-715 and 749 onwards.

Referee comment 18: "Specific comments" addressing the scientific issues including but not limited to the above general overarching comments with the modeling approach and analysis to be addressed, are all listed in detail in the attached Supplement (gmd-2018-255_RC2.pdf).

Answer 18: *Thank you for the specific comments. We revised the manuscript accordingly.*

Changes in manuscript 18: We substantially updated the manuscript and also addressed all the specific comments in the text and restructured parts of the text for clarity, for example chapter 2, which now more clearly addresses and explains all the implemented processes related to tillage and residue management.

- We corrected all the equations to use the same terminology as in previous model description papers of LPJmL (Schaphoff et al., 2018, von Bloh et al., 2018) and now also account for N pools, see for example chapter 3.2.
- We also specified more clearly if we only refer to the C part in SOM and included organic matter specific conversion factors from C to OM for litter (chapter 3.3.1, line 235 and from SOC to SOM (chapter 3.5.1, line 342).
- We have now named chapter 3.3.1 “litter interception”.
- We merged the previous chapters on bulk density and reconsolidation to one chapter 3.5.2 to better acknowledge the implemented process taken from the APEC/EPIC approach and refer to the first publication of the EPIC model from Williams et al. (1983).
- We revised and added explanations and possible source of uncertainty of the modeled results to the general discussion.

- We have revised and extended the discussion in chapter 5.5 on N_2O fluxes in order to better explain the variabilities and related processes of N_2O emission, also explained by changes in soil moisture (line 633 onwards).
- In terms a variability and the effect of residual inputs to SOM we updated chapter 5.3 to better explain now the feedbacks and mechanism of increased soil and litter C over time.

Additional changes to the manuscript not requested by the referees:

- We updated table 1 and added simulation descriptions for the bare soil experiments
- We updated table 2 since we accidentally reported the wrong values in the previous manuscript
- We updated table 3 and removed some references we found not suitable (e.g. Steiner 1989)
- We added Fig. 2 for yield changes and aridity analysis
- We updated and reordered functions (18) to (24) in chapter 3.5.1 for better clarity

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Simulating the effect of tillage practices with the global ecosystem model LPJmL (version 5.0-tillage)

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Abstract. The effects of tillage on soil properties ~~(e.g. soil carbon and nitrogen),~~, crop productivity, and global greenhouse gas emissions have been discussed in the last decades. Global ecosystem models ~~are limited in simulating tillage.~~have limited capacity to simulate the various effects of tillage. With respect to the decomposition of soil organic matter, they either assume a constant increase due to tillage, or they ignore the effects of tillage. Hence, they do not allow for analyzing the effects of tillage and cannot evaluate, for example, reduced-tillage or no-till as mitigation practices for climate change. In this paper, we describe the implementation of tillage related practices in the global ecosystem model LPJmL. The extended model is ~~subsequently~~ evaluated against reported differences between tillage and no-till management on several soil properties. To this end, simulation results are compared with published meta-analysis on tillage effects. In general, the model is able to reproduce observed tillage effects on global, as well as regional patterns of carbon and water fluxes. However, modelled N-fluxes deviate from the literature and need further study. The addition of the tillage module to ~~LPJmL 5.0~~LPJmL5 opens opportunities to assess the impact of agricultural soil management practices under different scenarios with implications for agricultural productivity, carbon sequestration, greenhouse gas emissions and other environmental indicators.

1 Introduction

Agricultural fields are tilled for various purposes, including seedbed preparation, incorporation of residues and fertilizers, water management and weed control. Tillage affects a variety of biophysical processes that affect the environment, such as greenhouse gas emissions or soil carbon sequestration and can ~~promote~~influence various forms of soil degradation (e.g. wind-, water- and tillage-erosion~~), leaching and runoff.~~) (Armand et al., 2009; Govers et al., 1994; Holland, 2004). Reduced-tillage or no-till is being promoted as a strategy to mitigate greenhouse gas (GHG) emissions in the agricultural sector (Six et al., 2004; Smith et al., 2008). ~~There~~However, there is an ongoing long-lasting debate about tillage and no-till effects on soil organic carbon (SOC) and GHG emissions (~~Schlüter~~e.g. Lugato et al., 2018). In general, reduced~~- or~~tillage and no-till ~~tends~~tend to increase SOC storage through a reduced decomposition and ~~thereby reducing~~consequently reduces GHG emissions (Chen et al., 2009; Willekens et al., 2014). ~~However, several field studies have shown contradictory results (Grandy et al., 2006; van Kessel et al., 2013; Lugato et al., 2018; Powlson et al., 2014; Zhao et al., 2016). This is~~However, discrepancies exist on the effectiveness of reduced tillage or no-till on GHG emissions. For instance, Abdalla et al. (2016), found in a meta-analyses that on average no-till systems reduce CO_2 emissions by 21% compared to conventional tillage, whereas Oorts et al. (2007) found that CO_2 emissions from no-till systems increased by 13% compared to conventional tillage, and Aslam et al. (2000) found only minor differences in CO_2 emissions. These discrepancies are not surprising as tillage affects a complex set of biophysical factors. The effect of reduced tillage or no-till impacts on SOC storage and GHG emissions varies depending on climate and, such as soil conditions that influence plantmoisture and soil temperature (Snyder et al., 2009), which drive several soil processes driving, including the carbon and nitrogen dynamics, and crop performance. Moreover, other factors such as management practices (e.g. fertilizer application and residue management) and climatic conditions have been shown to be important confounding factors (Abdalla et al., 2016; Oorts et al., 2007; van Kessel et al., 2013). For instance Oorts et al. (2007) attributed the higher CO_2 emissions under no-till to higher soil moisture and decomposition (Díaz-Zorita et al., 2002;of crop litter on top of the soil. Van Kessel et al. (2013) found that N_2O emissions were smaller under no-till in dry climates and that the depth of fertilizer application was important. Finally, Abdalla et al. (2016) found that no-till effects on CO_2 emissions are most effective in dryland soils. Ogle et al., 2005).

In order to upscale this complexity and to study the role of tillage for global biogeochemical cycles, crop performance and mitigation practices, the effects of tillage on soil physical properties need to be represented in global ecosystem models. ThoughAlthough tillage is already implemented in other ecosystem models in different levels of complexity (Lutz et al., under review2019; Maharjan et al., 2018), tillage practices in global ecosystem models are currently underrepresented in global ecosystem models that are used for biogeochemical assessments. In these, the effects of tillage are either ignored, or represented by a simple scaling factor of decomposition rates. Global ecosystem models that ignore the effects of tillage include for example JULES (Best et al., 2011; Clark et al., 2011) , the Community Land Model (Levis et al., 2014; Oleson et al., 2010) PROMET (Mauser and Bach, 2009) and the Dynamic Land Ecosystem Model (DLEM) (Tian et al., 2010). . The models in which the effects of tillage are represented as an increase in decomposition include LPJ-GUESS (Olin et al., 2015; Pugh et al., 2015) and ORCHIDEE-STICS (Ciais et al., 2011).

This The objective of this paper describes new routines as implemented intois to 1) extend the Lund Potsdam Jena managed Land (LPJmL5) model (von Bloh et al., 2018) that), so that the effects of tillage on biophysical processes and global biogeochemistry can be represented and studied and 2) evaluate the extended model against data reported in meta-analyses by using a set of stylized management scenarios. This extended model version allows for studying different tillage practices. This enables us to quantifyquantifying the effects of different tillage practices on biogeochemical cycles, crop performance and for assessing questions related to agricultural mitigation practices. Despite uncertainties in the formalization and parameterization of processes the processed-based representation allows for enhancing our understanding of the complex response patterns as individual effects and feedbacks can be isolated or disabled to understand their importance. To our knowledge, some crop models that have been used at the global scale, EPIC (Williams et al., 1983) and DSSAT (White et al., 2010), have similarly detailed representations of tillage practices, but models used to study the global biogeochemistry (Friend et al., 2014) have no or only very coarse representations of tillage effects.

2 Tillage effects on soil processes

Tillage affects different soil properties and soil processes, which resultresulting in a complex system with various feedbacks on soil water, temperature and carbon (C) and nitrogen (N) related processes (Fig. 1). Some processes are not taken into account in this initial implementation (e.g. soil compaction and water erosion) to limit model complexity, despite acknowledging that these processes can be important.

1). The effect of tillage has to be implemented and analyzed in conjunction with residue management as these management practices are often inter-related. The degree to which properties and processes are affected mainly depends on the tillage intensity. We here describe few selected processes (identified by numbered elements in Fig. 1), without distinguishing tillage intensities, even though these can be parametrized in LPJmL.The processes that were implemented into the model were chosen based on the importance of the process and its compatibility with the implementation of other processes within the model. Those processes are visualized in Fig. 1 with solid lines; processes that have been ignored in this implementation are visualized with dotted lines. To illustrate the complexity, we here describe selected processes in the model affected by tillage and residue management, using the numbered lines in Fig. 1.

The presence of a residue layer on top of the soil column tends to increase water infiltration [1] by intercepting part of the rainfall, limiting soil crusting and reducing runoffWith tillage, surface litter is incorporated (Ranaivoson et al., 2017). Moreover, it tends to lower soil evaporation [2] and to reduce the amplitude of soil temperature [3] (Enrique et al., 1999; Steinbach and Alvarez, 2006). Incorporating residues into the soil [1] and increases the soil organic matter (SOM) content of the tilled soil layer [42], while tillage also decreases the bulk density of the tilled soilthis layer is decreased [5[3] (Green et al., 2003). An increase in SOM will positively affectaffects the porosity [4] and therefore the soil water holding capacity (WHC) [6whc) [5] (Minasny and McBratney, 2018). The result of a decrease in bulk densityTillage also affects the WHC through thewhc by increasing porosity [76]. A change in WHCwhc affects several water--related processes. through soil moisture [7]. For instance, an increasechanges in WHC reducessoil moisture influence lateral runoff [8] and leaching [8], whereas9] and affect infiltration. A wet (saturated) soil for example decreases infiltration [10], while infiltration can be enhanced asif the soil can store more soilis dry. Soil moisture [9],affects primary production as it determines the amount of water which is beneficial for available for the plants [11] and changes in plant productivity again determine the amount of residues left at the soil surface or to be incorporated into the soil [1] (feedback not shown).

The presence of crop residues on top of the soil (referred to as "surface litter" hereafter) enhances water infiltration into the soil [12], and thus increases soil moisture [13]. That is because surface litter limit soil crusting, can constitute preferential pathways for water fluxes and slows lateral water fluxes at the soil surface so that water has more time to infiltrate. Consequently, surface litter reduces surface runoff [14] (Ranaivoson et al., 2017). Surface litter also intercepts part of the rainfall [15], reducing the amount of water reaching the soil surface, but also lowers soil evaporation [16] and thus reduces unproductive water losses to the atmosphere. Surface litter also reduces the amplitude of variations in soil temperature [17] (Enrique et al., 1999; Steinbach and Alvarez, 2006). access to water [10]. The soil temperature is strongly related to soil moisture [1118], through the heat capacity of the soil, i.e. a relatively wet soil heats up much slower than a relatively dry soil (Hillel, 2004). Changes in soil moisture and soil temperature influence several processes, including the The rate of SOM mineralization [12].is influenced by changes in soil moisture [19] and soil temperature [20]. The rate of mineralization affects the amount of CO_2 emitted from soils [1321] and the inorganic N content of the soil.

Inorganic N can then be taken up by plants [1422], be lost as N_2O [15gaseous N [23], or transformed ininto other forms of N (not shown). After the soil has been tilled, due. The processes of nitrate (NO_3^-) leaching, nitrification, denitrification, mineralization of SOM and immobilization or mineral N forms are explicitly represented in the model (von Bloh et al., 2018). The degree to gravitational forces and which soil properties and processes are affected by tillage mainly depends on the tillage intensity, which is a combination of tillage efficiency and mixing efficiency (in detail explained in chapter 3.2 and 3.5.2). Tillage has a direct effect on the bulk density of the tilled soil layer. The type of tillage determines the mixing efficiency, which affects the amount of incorporating residues into the soil. Over time, soil properties reconsolidate after tillage, eventually returning to pre-tillage states. The speed of reconsolidation depends on soil texture and the kinetic energy of precipitation, the soil over time consolidates, which means it slowly returns to its (Horton et al., 2016).

This implementation mainly focuses on two processes directly affected by tillage: 1) the incorporation of surface litter associated with tillage management and the subsequent effects (Fig. 1, arrow 1 and following arrows), 2) the decrease in bulk density and the subsequent effects of changed soil water properties (Fig. 1, e.g. arrow 3 and following arrows). In order to limit model complexity and associated uncertainty, tillage effects that are not directly compatible with the original density level before it was tilledmodel structure such as subsoil compaction or require very high spatial resolution, which renders it unsuitable for global-scale simulations, such as water erosion, are not taken into account in this initial tillage implementation, despite acknowledging that these processes can be important.

[Fig. 1]

3 Implementation of tillage routines into LPJmL

3.1 LPJmL model description

The tillage implementation described in this paper was introduced into the dynamical global vegetation, hydrology and crop growth model LPJmL (version 5), which . This model was recently extended by a to also cover the terrestrial N cycle to also account, accounting for nutrient limitations (N dynamics in soils and plants and N limitation of plant growth (LPJmL5; von Bloh et al., 2018). Previous comprehensive model descriptions and developments can be found in are described by Schaphoff et al. (20182018a). The LPJmL model simulates the C, N and water cycles and explicitby explicitly representing biophysical processes in plants (e.g. photosynthesis) and soilsoils (e.g. mineralization of N and C). The water cycle explicitly considersis represented by the processes of rain water interception, soil and lake evaporation, plant transpiration, soil infiltration, lateral and surface runoff., percolation, seepage, routing of discharge through rivers, storage in dams and reservoirs and water extraction for irrigation and other consumptive uses.

In LPJmL5, all organic matter pools (vegetation, litter and soil) are represented as C pools and the corresponding N pools with variable C:N ratios. Carbon, water and N pools in vegetation and soils are updated daily as the result of computed processes (e.g. photosynthesis, autotrophic respiration, growth, transpiration, evaporation, infiltration, percolation, mineralization, nitrification, leaching; see von Bloh et al. (2018) for the full description. Litter pools are represented by the above-ground pool (e.g. crop residues, such as leaves and stubbles) and the below-ground pool (roots). The litter pools are subject to decomposition, after which the humified products are transferred to the two SOM pools that have different decomposition rates (Appendix 1A).

The fraction of litter which is harvested from the field can range between almost fully harvested or none, when all litter is left on the field (90%, Bondeau et al., 2007). In the soil, pools of inorganic reactive N forms (NH_4^+, NO_3^-) are also considered. Each organic soil pool consists of C and N pools and the resulting C:N ratios are flexible. Soil C:N ratios are considerably smaller than those of plants as immobilization by microorganisms concentrates N in SOM. In LPJmL, as soil C:N ratio of 15 is targeted by immobilization for all soil types (von Bloh et al., 2018). The SOM pools in the soil consist of a fast pool with a turnover time of 30 years, and a slow pool with a 1000 year turnover time (Schaphoff et al., 2018a). Soils in ~~LPJmL~~LPJmL5 are represented by five hydrologically active layers, each with a distinct layer thickness. The first soil layer, which is mostly affected by tillage, is 0.2 m ~~deep~~thick. The following soil layers are 0.3, 0.5, 1.0 and 1.0 m thick, respectively, followed by a 10.0 m bedrock layer~~.~~, which serves as a heat reservoir in the computation of soil temperatures (Schaphoff et al. 2013).

~~In LPJmL5, all organic matter pools are represented as C and N pools with variable C:N ratios (Appendix Fig. 5a). The fraction of residues, which are harvested, can range between almost fully harvested (90%, Bondeau et al. 2007) or none, when all residues are left on the field. The C and N content in the residues that are not harvested (>10%) are transferred to the above-ground litter pool ($Litter_{ag}$). The C and N content in crop roots are transferred to the below-ground litter pool ($Litter_{bg}$). The litter pools are then subject to decomposition, after which the humified products are transferred to one of the SOM pools. The SOM pools consist of a fast pool with a turnover time of 30 years, and a slow pool with a 1000 year turnover time (Schaphoff et al., 2018). Carbon, water and N pools in vegetation and soils are updated daily as the result of computed processes (photosynthesis, autotrophic respiration, growth, transpiration, evaporation, infiltration, percolation, mineralization, nitrification, leaching and many more; for a full description see Bloh et al. (2018)). LPJmL5 has been evaluated extensively and demonstrated that the model performs credibly for reproducing C, water and N fluxes in both agricultural and natural vegetation on various scales (Bloh et al., 2018; Schaphoff et al., 2018b).~~

LPJmL5 has been evaluated extensively and demonstrated good skill in reproducing C,- water and N fluxes in both agricultural and natural vegetation on various scales (Bloh et al., 2018; Schaphoff et al., 2018b).

3.2 Litter pools and decomposition

In order to ~~take care of~~address the residue management ~~resulting to~~effects of tillage, ~~we have introduced~~the original above-ground litter pool is now separated into an incorporated litter pool (~~$Litter_{inc}$~~)$C_{litter,inc}$) and a surface litter pool ~~($Litter_{surf}$).~~($C_{litter,surf}$) for carbon, and the corresponding pools ($N_{litter,inc}$) and ($N_{litter,surf}$) for nitrogen (Appendix 1B). Crop residues not collected from the field are transferred to ~~$Litter_{surf}$.~~the surface litter pools. A fraction of residues from ~~$Litter_{surf}$~~ the surface litter pool is then partially or fully transferred to the incorporated litter ~~pool ($Litter_{inc}$),~~pools, depending on the tillage practice;

~~$Litter_{inc} = Litter_{inc} + Litter_{surf} \cdot TL,$ (1)~~

~~and the $Litter_{surf}$ pool is~~ $C_{litter,inc,t+1} = C_{litter,inc,t} + C_{litter,surf,t} \cdot TL,$ for carbon , and (1)

$N_{litter,inc,t+1} = N_{litter,inc,t} + N_{litter,surf,t} \cdot TL,$ for nitrogen.

The $C_{litter,surf}$ and $N_{litter,surf}$ pools are reduced accordingly~~;~~:

$$\sout{Litter_{surf} = Litter_{surf}} C_{litter,surf,t+1} = C_{litter,surf,t} \cdot (1 - TL), \quad (2)$$

$$N_{litter,surf,t+1} = N_{litter,surf,t} \cdot (1 - TL),$$

where ~~$litter_{inc}$~~$C_{litter,inc}$ and $N_{litter,inc}$ is the amount of incorporated surface litter C and N ~~(treated separately but accounting for actual C:N ratios of the pools)~~ in g m^{-2} ~~after tillage.~~at time step t (days). The parameter TL is the tillage efficiency, which determines the fraction of residues ~~which are~~that is incorporated by tillage (0-1). To account for the vertical displacement of litter through bioturbation under natural vegetation and under no-till conditions, we assume that 0.~~2~~1897% of the ~~$Litter_{surf}$~~surface litter pool is transferred to ~~$Litter_{inc}$~~the incorporated litter pool per day (equivalent to an annual bioturbation rate of 50%).

~~$Litter_{inc}$ and $Litter_{surf}$~~ The litter pools are subject to decomposition. ~~The decomposition of $Litter_{inc}$ depends on soil moisture and temperature of the first soil layer, similar to $Litter_{ag}$ as described in Schaphoff et al. (2018). The decomposition of $Litter_{surf}$ is described below.~~

~~3.2.2 Decomposition~~

The decomposition of litter depends on the temperature and moisture of its surroundings. ~~For the litter pools within the soil column ($Litter_{bg}$ and $Litter_{inc}$) decomposition~~ The decomposition of the incorporated litter pools depends on soil moisture and temperature of the first soil layer (as described by von Bloh et al., 2018), whereas the decomposition of the surface litter pools depends on ~~soil~~the litter's moisture and ~~soil~~ temperature~~ of the upper soil layer, whereas the decomposition of the $Litter_{surf}$ depends on its own temperature and moisture~~, which are approximated by the model. The decomposition rate of litter ($rdecom$ in g C m^{-2} day^{-1}) is described by first-order kinetics, and is specific for each "plant functional type" (PFT), following Sitch et al. (2003);

$$rdecom_{(PFT)} = 1 - exp(-\frac{1}{\tau_{10(PFT)}} \cdot g(T_{surf}) \cdot F(\Theta)), \quad (3)$$

where τ_{10} is the mean residence time for litter and $F(\Theta)$ and $g(T_{surf})$ are response functions of the decay rate to litter moisture and litter temperature (T_{surf}) respectively. ~~(Eq. (5), (12)). As the litter decomposes, a~~ The response function to litter moisture $F(\Theta)$ is defined as;

$$F(\Theta) = 0.0402 - 5.005 \cdot \Theta^3 + 4.269 \cdot \Theta^2 + 0.7189 \cdot \Theta \quad (4)$$

where, Θ is the volume fraction of litter moisture which depends on the water holding capacity of the surface litter (whc_{surf}), the fraction of surface covered by litter (f_{surf}), the amount of water intercepted by the surface litter (I_{surf}) (chapter 3.3.1) and lost through evaporation E_{surf} (chapter 3.3.3).

The temperature function $g(T_{surf})$ describes the influence of temperature of surface litter on decomposition (von Bloh et al., 2018);

$$g(T_{surf}) = exp(308.56 \cdot (\frac{1}{66.02} - \frac{1}{(T_{surf+56.02})})) \qquad (5)$$

Where T_{surf} is the temperature of surface litter (chapter 3.4).

A fixed fraction (70%) of the Cdecomposed $C_{litter,surf}$ is mineralized, i.e., emitted as CO_2 (70%),, whereas the remaining humified C is transferred to the soil C pools following, where it is then subject to the usual litter and soil decomposition rules as described by von Bloh et al. (2018) and Schaphoff et al. (20182018a). The mineralized N (also 70%)% of the decomposed litter) is added to the ammonium NH_4^+pool of the first soil layer, where it is subjected to further transformation transformations (von Bloh et al., 2018), whereas the humified organic N (30% of the decomposed litter) is allocated to the different organic soil N pools in the same shares as the humified C. TheIn order to maintain the desired C:N ratio of 15 within the soil (von Bloh et al., 2018), the mineralized N is subject to microbial immobilization, i.e., the transformation of mineral N to organic N directly reverting some of the N mineralization in the soil.

The presence of surface litter influences the soil water fluxes and soil temperature of the soil (see 3.3 and 3.4), and therefore affects the decomposition of litter *decom* (in g C m^{-2} day^{-1}) is described by first-order kinetics (Eq. 3), following Sitch et al. the soil carbon and nitrogen pools, including the transformations of mineral N forms. Nitrogen fluxes such as N_2O from nitrification and denitrification for instance, are partly driven by soil moisture (von Bloh et al., 2018):(2003);

$$decom = Litter \cdot (1 - e^{-(k \cdot response)}), \qquad (3)$$

where k is a decomposition rate in day^{-1} (specific for each "plant functional type") and $response$ the litter response function, which depends on the litter temperature (T_{litter} in °C) and litter moisture (S in mm);

$$response = T_{litter} \cdot (0.04021601 - 5.00505434 \cdot (S^3) + 4.26937932 \cdot (S^2) + 0.71890122 \cdot S). \qquad (4)$$

T_{litter} is calculated as an average of soil temperature and air temperature. S depends on the water holding capacity of the litter layer (WHC_{litter}), the fraction of residue cover ($Cover_{surf}$) and the amount of water captured by the litter layer ($Infil_{surf}$).

$$F_{N2O,nitrification,l} = K_2 \cdot K_{max} \cdot F_1(T_l) \cdot F_1(W_{sat,l}) \cdot F(pH) \cdot NH_{4,l}^{+} \text{ for nitrification, and} \qquad (6)$$

$$F_{N2O,denitrification,l} = r_{mx2} \cdot F_2(W_{sat,l}) \cdot F_2(T_l, C_{org}) \cdot NO_{3,l}^{-} \text{ for denitrification.}$$

Where $F_{N2O,nitrification}$ and $F_{N2O,denitrification}$ are the N_2O flux related to nitrification and denitrification respectively in gN m^{-2} d^{-1} in layer l. K_2 is the fraction of nitrified N lost as N_2O ($K_2 = 0.02$), K_{max} is the maximum nitrification rate of NH_4^+ ($K_{max} = 0.1\ d^{-1}$). $F_1(T_l)$, $F_1(W_{sat,l})$, are response functions of soil temperature and water saturation respectively, that limit the nitrification rate. $F(pH)$ is the function describing the response of nitrification rates to soil pH and $NH_{4,l}^{+}$ and $NO_{3,l}^{-}$ the soil ammonium and nitrate concentration in gN m^{-2} respectively. $F_2(T_l, C_{org})$, $F_2(W_{sat,l})$ are reaction for soil temperature, soil carbon and water saturation and r_{mx2} is the fraction of denitrified N lost as N_2O (11%, the remainder is lost as N_2). For a detailed description of the N related processes implemented in LPJmL, we refer to von Bloh et al. (2018).

3.3 Water fluxes

3.3.1 Litter ~~infiltration~~interception

Precipitation and applied irrigation water in LPJmL5 is partitioned into interception, transpiration, soil evaporation, soil moisture and runoff (Jägermeyr et al., 2015). To account for the interception and evaporation of water by ~~the~~ surface ~~cover~~litter, the water can now also be captured by ~~$Litter_{surf}$ by infiltration ($Infil_{surf}$~~surface litter through litter interception (I_{surf}) and be lost through litter evaporation~~. Surplus water that cannot infiltrate into the $Litter_{surf}$ layer, i.e. more than WHC_{litter}~~, subsequently infiltrates into the ~~first~~ soil ~~layer.~~and/or forms surface runoff. Litter moisture (~~S~~Θ) is calculated in the following way:

~~$$S_{(t+1)} = \min(WHC_{litter} - S_{(t)}, Infil_{surf} \cdot Cover_{surf}). \quad (5)$$~~

~~$Cover_{surf}$~~
$$\Theta_{t+1} = \min(whc_{surf} - \Theta_{(t)}, I_{surf} \cdot f_{surf}). \quad (7)$$

f_{surf} is calculated by adapting the equation from Gregory (1982) that relates the amount of ~~residues~~surface litter (dry matter) per m^2 to the fraction of soil covered by crop residue;

~~$$Cover_{surf} = 1 - exp^{-A_m \cdot Litter_{surfOM}}, \quad (6)$$~~

$$f_{surf} = 1 - exp^{-A_m \cdot OM_{litter,surf}}, \quad (8)$$

where ~~$Litter_{surfOM}$~~$OM_{litter,surf}$ is the total mass of dry matter ~~residues~~surface litter in g m^{-2} and A_m is the area covered per mass of crop specific residue (m^2 g^{-1}). The total mass of ~~residues is calculated in the following way:~~surface litter is calculated assuming a fixed C to organic matter ratio of 2.38 ($CF_{OM,litter}$), based on the assumption that 42% of the organic matter is C, as suggested by Brady and Weil (2008):

~~$$Litter_{surfOM} = Litter_{surfC} \cdot CF_{SOM}, \quad (7)$$~~

~~where $Litter_{surfOM}$ is the total mass of residues in g SOM m^{-2}, $Litter_{surfC}$ is the amount of C stored in $Litter_{surf}$ in g C m^{-2}. To get the total amount of SOM in $Litter_{surfOM}$, we apply a factor of 2 (CF_{SOM}), based on the assumption that organic matter is 50% C, as in Pribyl (2010).~~
$$OM_{litter,surf} = C_{litter,surf} \cdot CF_{OM,litter}, \quad (9)$$

where $C_{litter,surf}$ is the amount of C stored in the surface litter pool in g C m^{-2}. We apply the average value of 0.004 for A_m from Gregory (1982) to all materials, neglecting variations in surface ~~cover~~litter for different materials. ~~WHC_{litter}~~WHC_{surf} (mm) is the water holding capacity of the surface litter and is calculated by multiplying the ~~WHC of~~ litter mass with a ~~kg~~conversion factor of ~~litter (set to~~ 2~~$\cdot 10^{-3}$~~ 10^{-3} mm kg^{-1} ~~SOM) with the litter mass ($Litter_{surfOM}$~~ ($OM_{litter,surf}$) following Enrique et al. (1999).

3.3.2 Soil infiltration

The presence of surface litter enhances infiltration of precipitation or irrigation water into the soil, as soil crusting is reduced and preferential pathways are affected (Ranaivoson et al., 2017). In order to account for improved infiltration with the presence of surface litter, we follow the approach by Jägermeyr et al. (2016), which has been developed for implementing in situ water harvesting, e.g. by mulching in LPJmL. The infiltration rate (In in mm d^{-1}) depends on the soil water content of the first layer and the infiltration parameter p:

$$In = prir \cdot \sqrt[p]{1 - \frac{W_a}{W_{sat,l=1} - W_{pwp,l=1}}}, \qquad (10)$$

where $prir$ is the daily precipitation and applied irrigation water in mm, W_a the available soil water content in the first soil layer, and $W_{sat,l=1}$ and $W_{pwp,l=1}$ the soil water content at saturation and permanent wilting point of the first layer in mm. By default $p = 2$, but four different levels are distinguished ($p = 3, 4, 5, 6$) by Jägermeyr et al. (2016), in order to account for increased infiltration based on the management intervention. To account for the effects of surface litter, we here scale this infiltration parameter between 2 and 6, based on the fraction of surface litter cover (f_{surf}):

$$p = 2 \cdot (1 + f_{surf} \cdot 2) \qquad (11)$$

Surplus water that cannot infiltrate forms surface runoff and enters the river system.

3.3.3 Litter and soil evaporation

Evaporation ($Evap_{Litter}$ E_{surf}, in mm) from $Cover_{surf}$, the surface litter cover (f_{surf}), is calculated in a similar manner as evaporation from the first soil layer where evaporation is a function of potential evapotranspiration (Schaphoff et al., 2018a). Evaporation depends on the vegetation cover (f_v), the radiation energy for the vaporation of water (PET), evaporation) and the water stored in the surface litter that is available water to evaporate (ω_{litter} ω_{surf}) relative to WHC_{litter}, vegetated cover ($Cover_{veg}$) and radiation energy (Schaphoff et al., 2018). whc_{surf}. Here, also $Cover_{surf}$ f_{surf} is taken into account so that the fraction of soil uncovered is subject to soil evaporation as described in Schaphoff et al. (2018 2018a);

$$\omega_{litter} = S/WHC_{litter}, \qquad (8)$$

$$Evap_{Litter}\, E_{surf} = PET \cdot \alpha \cdot \max(1 - Cover_{veg}\, f_v, 0.05) \cdot \omega^2_{Litter}\, \omega^2_{surf} \cdot Cover_{surf}, \; (9)\; f_{surf}, \qquad (12)$$

$$\omega_{surf} = \Theta / WHC_{surf}, \qquad (13)$$

where PET is calculated based on the theory of equilibrium evapotranspiration (Jarvis and McNaughton, 1986) and α the empirically derived Priestley-Taylor coefficient ($\alpha = 1.32$) (Priestley and Taylor, 1972).

The presence of ~~$Cover_{surf}$~~ litter at the soil surface reduces the evaporation ~~of a soil layer ($Evap_{soil}$). $Evap_{soil}$ (mm) occurs when there is not a full $Cover_{surf}$ ($Cover_{surf} < 1$). $Evap_{soil}$~~ from the soil (E_{soil}). E_{soil} (mm) corresponds to the soil evaporation as described in Schaphoff et al. ~~(2018), where $Evap_{soil}$~~ (2018a), and depends on the available energy for vaporization of water and the available water in the upper 0.3 m of the soil (ω_{evap}). However, with the implementation of tillage, the fraction of ~~$Cover_{surf}$~~ f_{surf} now also influences evaporation, i.e~~, a larger fraction of $Cover_{surf}$~~., greater soil cover (f_{surf}) results in a decrease in ~~$Evap_{soil}$.~~ E_{soil}~~:~~

$$E_{soil} = PET \cdot \alpha \cdot \max(1 - f_v, 0.05) \cdot \omega^2 \cdot (1 - f_{surf}) \qquad (14)$$

ω is calculated as the evaporation-available water (ω_{evap}) relative to the water holding capacity in that layer (WHC_{evap});

$$\omega = \min\left(1, \frac{\omega_{evap}}{WHC_{evap}}\right), \qquad (~~10~~15)$$

where ω_{evap} is all the water above wilting point of the upper ~~layer (0.2 m) and one third of the second layer (~~0.3 m~~)~~ (Schaphoff et al., ~~2018);~~ 2018a).

~~$$Evap_{soil} = PET \cdot \alpha \cdot \max(1 - cover_{veg}, 0.05) \cdot \omega^2 \cdot (1 - Cover_{surf}). \qquad (11)$$~~

3.4 Heat flux

The temperature of the surface litter ~~layer~~ is calculated as the average of soil temperature of the previous day (t) of the first layer ~~($T_{soil,l=1}$~~ ($T_{soil,l=1}$ in°C) and actual air temperature (~~T_{air} in~~ $T_{air,t+1}$ in°C), in the following way:

~~$$T_{litter} = 0.5(T_{air} + T_{l=1}). \qquad (12)$$~~

$$T_{litter,surf,t+1} = 0.5(T_{air,t+1} + T_{l=1,t}). \qquad (16)$$

Equation (~~12~~16) is an approximate solution for the heat exchange described ~~in~~by Schaphoff et al. (2013). ~~In contrast to Schaphoff et al. (2013), the~~ The new upper boundary condition (T_{upper} in °C) is ~~no longer equal to T_{air}, but is~~ now calculated by the ~~$Cover_{surf}$ weighted~~ average of T_{air} and ~~T_{litter}:~~ T_{surf} weighted by f_{surf}. With the new boundary condition, the cover of the soil with surface litter diminishes the heat exchange between soil and atmosphere;

$$T_{upper} = \sout{T_{air} \cdot (1 - Cover_{surf}) + T_{litter} \cdot Cover_{surf}.} \qquad \sout{(13)}$$
$$T_{air} \cdot (1 - f_{surf}) + T_{surf} \cdot f_{surf}. \qquad (17)$$

The remainder of the soil temperature computation remains unchanged from the description of Schaphoff et al. (2013).

3.5 Tillage effects on physical properties

3.5.1 Hydraulic Dynamic calculation of hydraulic properties

Previous versions of the LPJmL model are usingused static soil hydraulic parameters as inputs, which were calculated usingcomputed following the pedotransfer function (PTF) by Cosby et al. (1984). We now introduced a new approach using the PTF by Saxton and Rawls (2006), which was included in the model in order to dynamically simulate permanent wilting point (PWP), field capacity (FC), saturation (SAT) and saturated hydraulic conductivity (Ks). Owing to the effects of changes in SOM on hydraulic characteristics and on soil productivity, we included a PTF which also takes organic matter content of the soil into account. Though severalDifferent methods exist to calculate feedbacks of SOM (Pachepsky and van Genuchten, 2011; Wösten et al., 1999) on soil hydraulic properties, we chose Saxton and Rawls (2006) since -to our knowledge- it was the only PTF where SOM feedbacks on those specific parameters were included. Other PTFs include from soil texture only (Cosbyand SOM content for different points of the water retention curve (Balland et al., 1984;2008; Saxton and Rawls, 2006; Wösten et al., 1982; Saxton et al., 19861999) or calculate SOM effects on soil water parameters at continuous pressure levels (Van Genuchten, 1980; Vereecken et al., 2010).

Dynamic soil water properties are now calculated on a daily time step via the PTF. The model considers twelve soil textural classes for productive soils, all with a specific percentage of silt, sand (Sa in %v) and clay (Cl in %v) and a 13th class for unproductive land, which is referred to as "rock and ice". The textural classes were derived following the approach by Cosby et al. (1984), who used the midpoint values of each textural class from the USDA textural Extensive reviews of PTFs and their application in Earth system and soil triangle to determine the average percentage of the soil separates sand, silt and clay. These percentages are then used in the PTF to calculate specific soil hydraulic properties for each textural class.modeling can be found in Van Looy et al. (2017) and Vereecken et al. (2016). We now introduced an approach following the PTF by Saxton and Rawls (2006), which was included in the model in order to dynamically simulate layer-specific hydraulic parameters that account for the amount of SOM in each layer, constituting an important mechanism of how hydraulic parameters are affected by tillage (Strudley et al., 2008).

PTF following Saxton and Rawls (2006):

PWP =As such, Saxton and Rawls (2006) define a PTF most suitable for our needs and capable of calculating all the necessary soil water properties for our approach: it allows for a dynamic effect of SOM on soil hydraulic properties, and is also capable of representing changes in bulk density after tillage and was developed from a large number of data points. With this implementation, soil hydraulic properties are now all updated daily. Following Saxton and Rawls (2006), soil water properties are calculated as:

$$\lambda_{pwp,l} = -0.024 \cdot Sa + 0.0487 \cdot Cl + 0.006 \cdot SOM_l + 0.005 \cdot Sa \cdot SOM_l - 0.013 \cdot Cl \cdot SOM_l + 0.068 \cdot Sa \cdot Cl + 0.031, \quad (18)$$

$$W_{pwp,l} = 1.14 \cdot \lambda_{pwp} \lambda_{pwp,l} - 0.02, \quad (1419)$$

$$\sout{FC =}\ \lambda_{fc,l} = -0.251 \cdot Sa + 0.195 \cdot Cl + 0.011 \cdot SOM_l + 0.006 \cdot Sa \cdot SOM_l - 0.027 \cdot Cl \cdot SOM_l + 0.452 \cdot Sa \cdot Cl + 0.299, \quad (20)$$

$$W_{fc,l} = 1.238 \sout{\cdot (\lambda_{fc})^2} \cdot (\lambda_{fc,l})^2 - 0.626 \cdot \sout{\lambda_{fc}} \lambda_{fc,l} - 0.015, \quad (15(21)$$

$$\sout{SAT = FC +}\ \lambda_{sat,l} = 0.278 \cdot Sa + 0.034 \cdot Cl + 0.022 \cdot SOM_l - 0.018 \cdot Sa \cdot SOM_l - 0.027 \cdot Cl \cdot SOM_l - 0.584 \cdot Sa \cdot Cl + 0.078, \quad (22)$$

$$W_{sat,l} = W_{fc,l} + 1.636 \cdot \sout{\lambda_{sat} -} \lambda_{sat,l} - 0.097 \cdot Sa - 0.064, \quad (16(23)$$

$$\sout{\lambda_{pwp,fc,sat} = \alpha \cdot Sa + \beta \cdot C + \gamma \cdot SOM + \delta \cdot Sa \cdot SOM + \varepsilon \cdot Cl \cdot SOM + \rho \cdot Sa \cdot Cl + \sigma,} \quad \sout{(17)}$$

$$\sout{BD =}\ BD_{soil,l} = (1 - \sout{SAT) \cdot} W_{sat,l}) \cdot MD. \quad (18(24)$$

~~[Table 1]~~

~~SOM~~SOM_l is the soil organic matter content in weight percent (%w~~), BD~~) of layer l, $W_{pwp,l}$ is the moisture content at the permanent wilting point, $W_{fc,l}$ moisture contents at field capacity, $W_{sat,l}$ is the moisture contents at saturation, $\lambda_{pwp,l}$, $\lambda_{fc,l}$ and $\lambda_{sat,l}$ are the moisture contents for the first solution at permanent wilting point, field capacity and saturation, Sa is the sand content in %v, Cl is the clay content in %v, $BD_{soil,l}$ is the bulk density in kg m^{-3}, MD is the mineral density of 2700 kg m^{-3}. ~~SOM is calculated using the slow and fast C pool as well as soil bulk density. This way, we ensure a feedback of organic material on soil water properties. SOM is calculated as~~For SOM_l, total SOC content is translated into SOM of this layer, following:

$$\sout{SOM = \frac{CF_{SOM} \cdot (SC_{fast} + SC_{slow})}{BD \cdot z}}\ SOM_l = \frac{CF_{OM,soil} \cdot (C_{fastSoil,l} + C_{slowSoil,l})}{BD_{soil,l} \cdot z_l} \cdot 100, \quad (19(25)$$

~~where SC_{fast}~~where $CF_{OM,soil}$ is the conversion factor of 2 as suggested by Pribyl (2010), assuming that SOM contains 50% SOC, $C_{fastSoil,l}$ is the fast decaying C pool in kg m^{-2}, ~~SC_{slow}~~$C_{slowSoil,l}$ is the slow decaying C pool in kg m^{-2} , ~~BD~~$BD_{soil,l}$ is the bulk density in kg m^{-3} and ~~z~~z is the thickness of ~~the specific soil~~ layer l in m. It was suggested by Saxton and Rawls (2006) that the PTF should not be used for ~~high SOM values,~~SOM content above 8%, so we ~~only consider SOM of up to 5%~~cap SOM_l at this maximum when computing soil hydraulic properties~~.~~ ~~We~~ and thus treated soils with ~~SOM~~SOM_l content above this threshold as soils with ~~5% SOM~~8% SOM content. Saturated hydraulic conductivity is also calculated ~~using the PTF from~~ following Saxton and Rawls (2006) ~~in the following way~~as:

$$\sout{Ks = 1930 \cdot (SAT - FC)^{3-\phi},} \quad \sout{(20)}$$

~~$\phi = \frac{\ln(FC)-\ln(PWP)}{\ln(1500)-\ln(33)}$~~ $Ks_l = 1930 \cdot \left(W_{sat_{(l)}} - W_{fc_{(l)}}\right)^{3-\phi_l}$, (26)

$$\phi_l = \frac{\ln(W_{fc,l})-\ln(W_{pwp,l})}{\ln(1500)-\ln(33)},$$ ~~(21~~(27)

where ~~Ks~~ Ks_l is the saturated hydraulic conductivity in mm h^{-1} and ~~ϕ~~ϕ_l is the slope of the logarithmic tension-moisture curve of layer l.

3.5.2 Bulk density effect and reconsolidation

~~Effects~~The effects of tillage ~~for the tillage layer~~ on BD are adopted from the APEX model by Williams et al. (2015) which is a follow-up development of the EPIC model (Williams et al., 1983). Tillage causes changes in BD of the tillage layer (first topsoil layer of 0.2 m) ~~are accounted for by adapting BD~~ after tillage~~, which is then used to calculate a new SAT and FC. Ks~~. Soil moisture content for the tillage layer is updated using the fraction of change in BD. Ks_l is also ~~newly calculated using SAT_{till} and FC_{till} in equation (23) and (24).~~updated based on the new moisture content after tillage. A mixing efficiency parameter (mE) depending on the intensity and type of tillage~~, which can be specified as a parameter and ranges between 0 and 1,~~ (0-1), determines the fraction of change in BD after tillage~~, following the APEX model approach (Williams et al., 2015). An~~. A mE of 0.90 for example represents a full inversion tillage practice, also known as conventional tillage (White et al., 2010). ~~Using~~The parameter mE can be used in combination with residue management ~~after harvest, we are now able~~assumptions to simulate different tillage types~~ and intensities, depending on the combination of settings. The BD change after tillage is following Williams et al. (2015):~~. It should be noted that Williams et al. (1983) calculate direct effects of tillage on BD, while we changed the equation accordingly to account for the fraction at which BD is changed.

The fraction of BD change after tillage is calculated the following way:

~~$f_{BDtill} = 1 - (1 - 0.667)$~~ $f_{BDtill,t+1} = f_{BDtill,t} - \left(f_{BDtill,t} - 0.667\right) \cdot mE.$ ~~(22~~(28)

Tillage density effects on saturation and field capacity follow Saxton and Rawls (2006):

~~$SAT_{till} = 1 - (1 - SAT_0) \cdot f_{BDtill},$ (23)~~

~~$FC_{till} = FC_0 - 0.2 \cdot (SAT_0 - SAT_{till}),$ (24)~~

$$W_{sat,till,l,t+1} = 1 - \left(1 - W_{sat,l,t}\right) \cdot f_{BDtill,t+1}, \quad (29)$$

$$W_{fc,till,l,t+1} = W_{fc,l,t} - 0.2 \cdot (W_{sat,l,t} - W_{sat,till,l,t+1}), \quad (30)$$

where ~~f_{BDtill}~~$f_{BDtill,t+1}$ is the fraction of density change of the topsoil layer after tillage, $f_{BDtill,t}$ is the density effect ~~on the top soil layer after~~before tillage, ~~SAT_{till}~~$W_{sat,till,l,t+1}$ and ~~FC_{till}~~$W_{fc,till,l,t+1}$ are adjusted moisture content at saturation and field capacity after tillage and ~~SAT_0 is the~~ $W_{sat,l,t}$ and $W_{fc,l,t}$ are the moisture content at saturation and field capacity before tillage.

~~3.5.3~~ Reconsolidation of ~~tillage effect~~

~~Depending on the structural composition of the soil and the amount of precipitation after the tillage event, with time~~ the tilled soil layer ~~reconsolidates to its state before tillage, also known as soil settling.~~ is accounted for following the same approach by Williams et al. (2015). The rate of reconsolidation depends on the rate of infiltration and the sand content of the soil. This ~~way~~ ensures that the porosity and BD changes caused by tillage gradually ~~decline, caused by a cycle of wetting and drying (Onstad et al., 1984). The reconsolidation of the soil is now accounted for using~~ return to their initial value before tillage. Reconsolidation is calculated the ~~approach by Williams et al. (2015) (Eqs. 25 to 27):~~ following way:

$$sz = 0.2 \cdot Infil_{soil} \cdot \frac{1+2\cdot Sa/(Sa+e^{8.597-0.075\cdot Sa})}{z_{till}^{0.06}} In \cdot \frac{1+2\cdot Sa/(Sa+e^{8.597-0.075\cdot Sa})}{z_{till}^{0.06}}, \quad (~~25~~ 31)$$

$$f = \frac{sz}{sz+e^{3.92-0.0226\cdot sz}}, \quad (~~26~~ 32)$$

~~$f_{BDtill(t+1)} = f \cdot (1 - f_{BDtill}),$ (27)~~

$$f_{BDtill,t+1} = f_{BDtill,t} + f \cdot (1 - f_{BDtill,t}), \quad (33)$$

where sz is the scaling factor for the tillage layer~~, $Infil_{soil}$ is the infiltration rate into the layer in mm d^{-1}~~ and z_{till} is the depth of the tilled layer in m. This allows for a faster settling of recently tilled soils with high precipitation and for soils with a high sand content. ~~In contrast soils with a low sand content settle slower, especially in dry areas with low precipitation.~~ In dry areas with low precipitation and for soils with low sand content, the soil settles slower and might not consolidate back to its initial state. This is accounted for by taking the previous bulk density before tillage into account. The effect of tillage on BD can vary from year to year, but $f_{BDtill,t}$ cannot be below 0.667 or above 1 so that unwanted amplification is not possible. We do not yet account for fluffy soil syndrome processes and negative implication from this, if the soil does not settle over the winter and spring time, which results in an unfavorable soil particle distribution that can cause a decline in productivity (Daigh and DeJong-Hughes, 2017).

4 Model setup

4.1 Model input, initialization and spin-up

In order to bring vegetation patterns and ~~*SOM*~~ SOM pools into a dynamic equilibrium stage, we make use of a 5000 years spin-up simulation of only natural vegetation, which recycles the first 30 years of climate input following the procedures of von Bloh et al. (2018). For simulations with land-use inputs and to account for agricultural management, a second spin-up of 390 years is conducted, to account for historical land-use change, which is introduced in the year 1700. The spatial resolution of all input data and model simulations is 0.5°. Land use data is based on crop-specific shares of MIRCA2000 (Portmann et al., 2010) and cropland and grassland time series since 1700 from HYDE3 (Klein Goldewijk et al., 2010) as described by Fader et al. (2010). As we are here interested in the effects of tillage on cropland, we ignore all natural vegetation in grid cells with cropland by scaling existing cropland shares to 100%. We drive the model with daily mean temperature from the Climate Research Unit (CRU TS version 3.23, University of East Anglia Climate Research Unit, 2015; Harris et al., 2014), monthly precipitation data from the Global Precipitation Climatology Centre (GPCC Full Data Reanalysis version 7.0; Becker et al., 2013~~), (~~) and shortwave downward and net longwave downward~~)~~ radiation data from the ERA-Interim data set (Dee et al., 2011). Static soil texture classes are taken from the Harmonized World Soil Database (~~Nachtergaele et al., 2009) and soil pH data~~HWSD) version 1.1 (Nachtergaele et al., 2009) and aggregated to 0.5° resolution by using the dominant soil type. Twelve different soil textural classes are distinguished according to the USDA soil texture classification and one unproductive soil type, which is referred to as "rock and ice". Soil pH data are taken from the WISE data set (Batjes, 2005). The NOAA/ESRL Mauna Loa station (Tans and Keeling, 2015) provides atmospheric CO_2 concentrations. Deposition of N was taken from the ACCMIP database (Lamarque et al., 2013).

4.2 Simulation options and evaluation set-up

The new tillage management implementation allows for specifying different tillage and residue systems. We conducted four contrasting simulations on current cropland area with or without the application of tillage~~. The effect~~ and with or without removal of ~~tillage on current cropland was evaluated.~~residues (Table 1). The default setting for conventional tillage is: mE=0.9 and TL=0.95. In the tillage scenario, tillage is conducted twice a year, at sowing and after harvest. Soil water properties are updated on a daily basis, enabling the tillage effect to be effective from the subsequent day onwards until it wears off~~. Four~~ due to soil settling processes. The four different management settings (~~MS~~MS) for global simulations ~~were used~~are as the following: 1) full tillage ~~performed~~ and ~~residue are~~residues left on the field (T_R), 2) full tillage ~~performed~~ and residues are removed (T_NR), 3) no-till and residues are retained on the field (NT_R), and 4) no-till and residues are removed from the field (NT_NR~~) (~~). The specific parameters for these four settings are listed in Table ~~2).~~1. The default MS is T_R and was introduced in the second spin-up from the year 1700 onwards, as soon as human land use is introduced in the individual grid cells (Fader et al. 2010). All of ~~these 4~~the four MS simulations were run ~~from the year 1900 until 2009. Land use was introduced in 1700 and with a spin-up simulation of 390~~for 109 years ~~for T_R after the spin-up simulation with 5000 years with natural vegetation only. We used fertilizer data supplied by the Global Gridded Crop Model Intercomparison (GGCMI phase 1; Elliott et al., 2015). Fertilizers are applied at sowing and when the amount of fertilizer is larger than 5 g N m^-2^, 50% is applied at sowing and 50% at a later stage in the growing season (depending on the phenological stage of~~, staring from year 1900. Unless specified differently, the ~~crop). From 1900 onwards the four new management options were introduced on current cropland. The~~ outputs of ~~these~~the four different MS simulations were analyzed using the relative differences between each output variable using T_R as the ~~default management;~~ baseline MS;

$$~~RD = \frac{MS}{T\_R}~~ \quad RD_X = \frac{x_{MS}}{x_{T\_R}} - 1, \qquad (~~28~~34)$$

where ~~RD~~ RD_X is the relative difference between the management scenarios~~.~~ for variable X and X_{MS} and X_{T_R} are the values of variable X of the MS of interest and the baseline management systems: conventional tillage with residues left on the field (T_R). Spin-up simulations and relative differences for equation (34) were adjusted, if a different MS was used as reference system, e.g. if reference data are available for comparisons of different MS. The effects were analyzed ~~using~~for different time scales: the three year average ~~after the first three years~~of year 1 to 3 for short-term effects, the average after year 9 to 11~~ years~~ for mid-term effects and the average of year 19 to 21 for long-term effects. Depending on available reference data in the literature, the specific duration and default MS of the experiment ~~was~~were chosen. The results of the simulations are compared to literature values from selected meta-analyses. Meta-analyses ~~were chosen in order to compare the~~allow for the comparison of globally modeled results to a set of combined results of individual studies from all around the world, ~~rather than choosing individual site-specific studies.~~assuming that the data basis presented in meta-analyses is representative. A comparison to individual site-specific studies would require detailed site-specific simulations making use of climatic records for that site and details on the specific land-use history. Results of individual site-specific experiments can differ substantially between sites, which hampers the interpretation at larger scales. We calculated the median and the 5th and 95th percentile (values within brackets) between MS in order to compare the model results to the meta-analyses, where averages and 95% confidence intervals (CI) are mostly reported. We chose medians rather than arithmetic averages to reduce outlier effects, which is especially important for relative changes that strongly depend on the baseline value. If region-specific values were reported in the meta-analyses, e.g. climate zones, we compared model results of these individual regions, following the same approach for each study, to the reported regional value ranges.

To analyze the effectiveness of selected individual processes (see Fig. 1) without ~~too many blurring~~confounding feedback processes, we conducted additional simulations of the four different ~~MS~~MS on bare soil with uniform dry matter litter input ~~of 75 g m^{-2}, 150 g m^{-2}~~(simulation NT_NR_bs and ~~300 g m^{-2}~~NT_R_bs1 to NT_R_bs5) of uniform composition (C:N ratio of 20), no atmospheric N deposition and static fertilizer input (Elliott et al~~.~~., 2015). This helps ~~to isolate~~isolating soil processes, as any feedbacks via vegetation performance is eliminated in this setting.

[Table ~~2]~~1]

5 Evaluation and discussion

5.1 Tillage effects on hydraulic properties

~~The~~Table 2 presents the calculated soil hydraulic properties of tillage for each of the soil classes prior to and after tillage ~~is performed~~(mE of 0.9), combined with ~~0% and 5% SOM~~ a SOM content in the ~~tillage~~tilled soil layer of 0% and ~~a mE of 0.9 (table 3).~~8%. In general, both tillage and a higher ~~SOM~~SOM content ~~have an increasing effect on WHC, SAT, FC~~tend to increase whc, $W_{sat,l}$, $W_{fc,l}$ and ~~Ks.~~Ks_l. Clay soils are an exception, since higher ~~SOM~~SOM content decreases ~~their WHC, SAT~~whc, $W_{sat,l}$ and ~~FC,~~$W_{fc,l}$, and increases ~~Ks. For~~Ks_l. The effect of increasing SOM content on whc, $W_{sat,l}$ and $W_{fc,l}$ is greatest in the soil classes sand and loamy sand~~, the increasing effect on WHC, SAT and FC of increasing SOM content shows be the highest among all classes, while Ks decrease with increasing SOM content~~. The increasing effects of tillage on the hydraulic properties are generally weaker compared to an increase in SOM by ~~5~~8% (maximum ~~SOM~~SOM content for computing soil hydraulic properties in the model). While tillage (mE of 0.9, 0% SOM) in sandy soils ~~with a mE~~increase whc by 83%, 8% of ~~0.9~~SOM can increase ~~WHC by 7%, an increase~~whc in ~~5% of SOM~~an untilled soil by 105% and in a tilled soil by 84%. As comparison in silty loam soils with 0% SOM, tillage (mE of 0.9) increases whc by 16%, while 8% SOM can increase ~~WHC by 27%.~~whc by 31% and by 26% for untilled and tilled soil, respectively.

The PTF by Saxton and Rawls (2006) uses an empirical relationship between ~~SOM~~SOM, soil texture and hydraulic properties derived from the USDA soil database, implying that the PTF is likely to be more accurate within the US than outside. A PTF developed for global scale application is, to our knowledge, not yet developed. Nevertheless ~~the PTF is~~PTFs are used in a variety of global applications, despite the limitations to validate ~~it~~ at ~~that~~this scale (Van Looy et al., 2017).

[Table ~~3~~2]

5.2 Productivity

In our simulations adopting NT_R slightly increases productivity for all rain-fed crops simulated (wheat, maize, pulses, rapeseed) on average, but ranges from increases to decreases across all cropland globally. This increase can be observed for the first three years (Appendix 2), and for the first ten years (Fig. 2A and 2B). The numbers discussed here refer to the productivity after 10 years (average of year 9-11). The largest positive impact can be found for rapeseed, where NT_R results in a median increase of +2.4 % (5^{th}, 95^{th} percentiles: -34.8%, +61.0%). The positive impact is lowest for maize, with median increases by +1.0% (5^{th}, 95^{th} percentiles: -34.2%, +55.6%). The median productivity of wheat increases slightly by +1.7% (5^{th}, 95^{th} percentiles: -24.4%, +54.8%) under NT_R. The slight increases in median productivity under NT_R are contrasting to the values reported by Pittelkow et al. (2015b), who reports slight decreases in productivity for wheat and maize and small median increases for rapeseed (Table 3). They report both positive and negative effects for wheat and rapeseed, but only negative effects for maize. Pittelkow et al. (2015b) identify aridity and crop type as the most important factors influencing the responses of productivity to the introduction of no-till systems with residues left on the field. The aridity index was determined by dividing the mean annual precipitation by potential evaporation. No-till performed best under rain-fed conditions in dry climates (aridity index <0.65), by which the overall response was equal or positive compared to T_R.

The positive effects on productivity under NT_R in dry regions can also be found in our simulations. For instance, wheat productivity increases substantially under NT_R whereas this effect diminishes with increases in aridity indexes (Fig. 2A). Similar results are found for maize productivity (Fig. 2B). This positive effect can be attributed to the presence of surface litter, which leads to higher soil moisture conservation through increased water infiltration into the soil and decreases in evaporation. Areas where crop productivity is limited by soil water could therefore potentially benefit from NT_R (Pittelkow et al., 2015a). The influence of climatic condition on no-till effects on productivity was already found by several other studies (e.g. Ogle et al., 2012; Pittelkow et al., 2015a; van Kessel et al., 2013). Ogle et al. (2012) found declines in productivity, but that these declines were larger in the cooler and wetter climates. Pittelkow et al. (2015a) found only small declines in productivity in dry areas, but emphasized that increases in yield can be found when no-till is combined with residues and crop rotation. This was not the case for humid areas (aridity index >0.65), there declines in productivity were larger under no-till regardless if residues and crop rotations were applied. Finally, van Kessel et al. (2013) found declines in productivity after adapting to no-till in dry areas (-11%) and humid areas (-3%). However, in their analysis it is not clear how crop residues are treated in no-till and tillage (i.e. removed or retained).

[Fig. 2]

5.3. Soil C stocks and fluxes

~~Model outputs~~We evaluate the effects of tillage and residue management on simulated soil C dynamics and fluxes for CO_2 emissions from cropland soils, relative change in C input, SOC turnover time as well as ~~*SOM*~~ relative changes in soil and litter C stocks of the topsoil (0.3 m~~) were used to evaluate the effects of tillage and residues management on soil C stocks and fluxes. ~~). In our simulation CO_2 emissions ~~and *SOM* response after~~ initially decrease for the average of the first three years by a median value of -11.8% (5th, 95th percentile: -24.5%, +2.1%) after introducing no-till (NT_R vs. T_R) (Appendix 3A) and soil and litter C stocks increase. After ten years duration ~~of NT_R MS compared to T_R show a discrepancy, as~~(average of year 9-11) however, both CO_2 emissions and ~~*SOM*~~ soil and litter C stocks ~~increase (Fig.~~ are higher under NT_R than under T_R (Fig. 3A, 3D). Median~~2A and 2B). The reported numbers refer to the median value across all cropland grid cells globally. After a duration of ten years of applied MS,~~ CO_2 emissions from NT_R compared to T_R ~~are increased~~increase by +~~2~~1.3% (5th, 95th percentile: ~~-9.6%, +29.0%) (Fig. 2A),~~22.1%, +32.8%), while at the same time median topsoil and litter C ~~is~~ also ~~increased~~increase by +~~5.7~~4.6% (5th, 95th percentile: +1.~~7%, +14%) (Fig. 2B),~~0%, +12.9%), i.e. the soil and litter C stock has already increased enough to sustain higher CO_2 emissions. ~~If we only look at the first three years after the change in MS,~~There are two explanations for CO_2 increase in the long term: 1) more C input from increased net primary production (NPP) for NT_R or 2) a higher decomposition rate over time under NT_R, due to changes in e.g. soil moisture or temperature. Initially CO_2 emissions ~~are substantially decreased by -12.2% (5th, 95th percentile: -18.3%, -2.8%) in a NT_R system~~ decrease almost globally due to increased turnover times under T_R (Appendix 3C), but after ten years, CO_2 emissions start to increase in drier regions, while they still decrease in most humid regions (Fig. 3A). The relative differences in mean residence time of soil carbon for NT_R compared to T_R are relatively small (+0.4% after ten years, 5th, 95th percentile: -23.2%, +29.2%) (Fig. 3C), but show similar patterns, i.e. the mean residence time decreases in drier areas but increases in more humid areas. The drier regions are also the areas where we observe a positive effect of reduced evaporation and increased infiltration on plant growth, i.e. in these regions the C-input into soils is substantially increased under NT_R compared to T_R (Fig. 3B) (see also 5.2 for productivity). As such, both mechanisms that affect CO_2 emissions are reinforcing each other in many regions. This is in agreement with the meta-analyses conducted by Pittelkow et al. (2015b), who report a positive effect on yields (and thus general productivity and thus C-input) of no-till compared to conventional tillage in dry climates. Their results show that in general, no-till performs best relative to conventional tillage under water-limited conditions, due to enhanced water-use efficiencies when residues are retained.

Abdalla et al. (2016) reviewed the effect of tillage, no-till and residues management and found if residues are returned, no-till compared to conventional tillage increases soil and litter C content by 5.0% (95th CI: -1.0%,

+9.2%) and an decreases CO_2 emissions from soils by -23% (95th CI: -35.0%, -13.8%) (Table 3). These findings of Abdalla et al. (Fig. 2D).are in line to our findings for CO_2 emissions if we consider the first three years of duration for CO_2 emissions and ten years duration for topsoil and litter C. Abdalla et al. (2016) do not explicitly specify a time of duration for these results. If we only analyze the tillage effect and do not takewithout taking residues into account, topsoil and litter C decreases by -9.9% (5th, 95th percentile: -27.0%, -0.6%) in a (T_NR system compared to a vs. NT_NR system after ten years (Appendix – Fig. 4A), while CO_2 emissions are increased by +), we find in our simulation that topsoil and litter C decreases by -17.13% (5th, 95th percentile: -43.0.%, -0%, +114.4%) (Appendix – Fig. 4B).

after twenty years, while CO_2 emissions increase by +20.9% (5th, 95th percentile: -1.2%, +125.8%) mostly in humid regions, whereas they start increasing in drier regions (Table 3). Abdalla et al. (2016) reviewed the effect of tillage, no-tillalso reported soil and residues managementlitter C changes from a T_NR vs. NT_NR comparison and they found that if residues are returned, tillage has a decreasing effect on topsoil *SOM* content by 5.reported a decrease in soil and litter C under T_NR of -12.0% (95th CI: -1.15.3%, -5.1%) and a CO_2 increase of +18.0%, +9.2%) and an increasing effect on CO_2 emissions +23% (95th CI: -35.0%, -13.8%) (Table +9.4%, +27.3%),). These findings of Abdalla et al. are in contradiction to our findings for CO_2 emissions after a ten year period, nevertheless if we only take the first three years duration of MS into account, CO_2 emissions are decreased as suggested by the literature. This supports the findings from Abdalla et al. (2016) and highlights the importance of accounting for the duration of the experiment after which the different MS are compared. Abdalla et al. (2016) also reported a decrease in *SOM* (-12%) and an increase in CO_2 emissions (+18%) of a T_NR system compared to a NT_NR system. T_NR was reported to decrease *SOM* content, while at the same time CO_2 emissions are increased, due to a higher soil temperatureis well in a tilled soil and an increased decomposition. The updated LPJmL reproduced these patterns.

A strong CO_2 response can be found in areas where *SOM* increases the most (e.g., northern Mexico and western Australia). This is also true for yields, here shown for maize yields after ten years of NT_R MS (Fig. 2C), which are mostly increasing in areasline with strong *SOM* increase (e.g., Argentina, mid-west USA, northeaster China and south-western Russia). These areas all have a warm temperate dry climate according to the IPCC climate zone classification (Carréour et al., 2010). This positive feedback could be driven by a positive water-savings effect from NT_R, where water which is saved due to NT_R leads to a higher productivity. NT_R for example reduces evaporation substantially compared to T_R and has other positive water-saving feedbacks, which are further discussed in chapter 5.3. In areas with higher productivity, we also have a higher residues input, since litter fall is a function of plant productivity (see Eq. (6)). If productivity feedbacks are disabled, using the simulation from a bare soil experiment, there is no difference in CO_2 emissions between NT_R and T_R (Appendix – Fig. 6).

Our simulations of NT_R and T_R show that NT_R has a positive effect on *SOM* (topsoil and litter) and this effect increases over time. Our model is generally reliable to reproduce *SOM* increase under NT_R for a duration of ten years and increasing CO_2 emissions under T_R for a duration of three years. Differences to literature estimates occur after ten years under NT_R with regard to CO_2 emissions because productivity feedbacks under NT_R are taken into account in our model. results.

Ogle et al. (2005) conducted a meta-analysis and reported *SOM*SOC changes from NT_R compared to T_R system with medium C input, grouped for different climatic zones. They found a +23%, +17%, + 16% and +10% mean increase in *SOM*SOC after converting from a conventional tillage to a no-till system for more than 20 years for tropical moist, tropical dry, temperate moist and temperate dry climates, respectively. We only find a +3.7%, +6.4%, +3.9% and +4.8% increase in topsoil and litter C for these regions, respectively. However, Ogle et al. (2005) analyzed the data ~~based~~by comparing a no-till system with high C inputs from rotation and residues to a conventional tillage system with medium C input from rotation and residues. We compare two similarly productive systems with each other, where residues are either left on ~~linear mixed-effect models,~~the field or incorporated through tillage (NT_R vs. T_R), which ~~do not account for interactions between effects. This could~~may explain why we ~~were not~~see smaller relative effects in the simulations. Comparing a high input system with a medium or a low input system will essentially lead to an amplification of soil and litter C changes over time; nevertheless we are still able to generally reproduce ~~these high numbers in *SOM* increase, since our model results range between a 5.1% to 11.9%~~ a SOC increase ~~in *SOM* after 20 years from tropical moist to temperate dry climates,~~over longer periods.

Unfortunately there are high discrepancies~~ respectively. LPJmL was also not able to reproduce the gradient found by Ogle et al. (2005). There is high discrepancy~~ in the literature ~~in~~with regard to no-till effects on ~~*SOM*~~soil and litter C, since the high ~~increase~~increases found by Ogle et al. (2005) ~~is~~are not supported by the findings of Abdalla et al. (2016). Ranaivoson et al. (2017) found that crop residues left on the field increases ~~*SOM*~~soil and litter C content, which is in agreement with our simulation results.

[Fig. ~~2~~3]

5.~~3~~4 Water fluxes

~~Water~~ We evaluate the effects of tillage and residue management on water fluxes by analyzing soil evaporation and surface runoff. Our results show that evaporation and surface runoff under NT_R compared to T_R are generally reduced by -43.7% (5th, 95th percentiles: -64.0, -17.4%) and by -57.6% (5th, 95th percentiles: -74.5%, -27.6%), respectively (Appendix 4A and 4B). We also analyzed soil evaporation and surface runoff for different amounts of surface litter and cover on bare soil without vegetation in order to compare our results to literature estimates from field experiments. We find that both the reduction in evaporation and surface runoff are dependent on the residue load, which translates into different rates of surface litter cover.

On the process side, water fluxes highly influence plant productivity and are affected by tillage and residue management (Fig. 1). ~~Residues~~Surface litter, which ~~are~~is left on the ~~soil~~ surface~~, create~~ of the soil, creates a barrier that reduces evaporation ~~from the soil. In addition, a residue cover effectively protects the soil surface from structural degradation through the impact of rain drops, thereby increasing rainfall~~ and also increases the rate of infiltration~~. Generally, residues,~~ into the soil. Litter which ~~are~~is incorporated into the soil through tillage~~, loose the~~ loses this function to cover the soil. Both, the reduction of soil evaporation and the increase of rainfall infiltration contribute to increased soil moisture and hence plant water availability. ~~protect the soil.~~ The model accounts for both processes. Scopel et al. (2004) modeled the effect of maize residues on soil evaporation calibrated from two tropical sites and found a presence of 100 g m^{-2} surface litter decrease soil evaporation by -10 to -15% in the data, whereas our model shows a median decrease in evaporation of -6.6% (5th, 95th percentiles: -26.1%, +20.3%) globally (Appendix 4C). The effect of a higher amount of surface litter is much more dominate, as Scopel et al. (2004) found that 600 g m^{-2} surface litter reduced evaporation by approx. -50%. For the same litter load our model shows a median decrease in evaporation by -72.6% (5th, 95th percentiles: -

81.5%, -49.1%) (Appendix 4D), which is higher than the results found by Scopel et al. (2004). We further analyze and compare our model results to the meta-analysis from Ranaivoson et al. (2017), who reviewed the effect of surface litter on evaporation and surface runoff and other agro-ecological functions. Ranaivoson et al. (2017) and the studies compiled by them not explicitly distinguish between the different compartments of runoff (e.g. lateral-, surface-runoff). We assume that they measured surface runoff, since lateral runoff is difficult to measure and has to be considered in relation to plot size. In Fig. 4, modeled global results for relative evaporation and surface runoff change for 10, 30, 50, 70 and 90% soil cover on bare soil are compared to literature values from Ranaivoson et al. (2017). Concerning the effect of soil cover on evaporation (Fig. 4A), we find that we are well in line with literature estimates from Ranaivoson et al. (2017) for up to 70% soil cover, especially when analyzing humid climates. For higher soil cover ≥70%, the model seems to more in line with literature values for arid regions. Overall for high soil cover of 90%, the model seems to overestimate the reduction of evaporation. It should be noted that the estimates from Ranaivoson et al. (2017) are only taken from two field studies, which are only representative for the local climatic and soil conditions, since global data on the effect of surface little on evaporation are not available. The general effect of surface litter on the reduction in soil evaporation is thus captured by the model, but the model seems to overestimate the response at high litter loads. It is not entirely clear from the literature if these experiments have been carried on bare soil without vegetation. If crops are also grown in the experiments, water can be used for transpiration which otherwise available for evaporation, which could explain why the model overestimates the effect of surface litter on evaporation on bare soil without any vegetation.

Ranaivoson et al. (2017) also investigated the runoff reduction under soil cover, but the results do not show a clear picture. In theory, surface litter reduces surface runoff and literature e generally supports this assumption (Kurothe et al., 2014; Wilson et al., 2008), but the magnitude of the effect varies. Fig. 4B compares our modeled results under different soil cover to the literature values from Ranaivoson et al. (2017). This shows that modeled results across all global cropland are on the upper end of the effect of surface runoff reduction from soil cover, but they are still well within the range reported by Ranaivoson et al. (2017).

[Fig. 4]

5.Both, the reduction of soil evaporation and the increase of rainfall infiltration contribute to increased soil moisture and hence plant water availability. Because we could not find suitable approaches to account for the processes leading to increased rainfall infiltration, our implementation only captures the reduction of soil evaporation. However, despite the significant increase in rainfall infiltration and corresponding reduction in surface runoff found in a number of field studies (Ranaivoson et al., 2017), the contribution to plant water availability is likely to be much smaller as a substantial portion of it will be lost through subsurface runoff (lateral runoff and seepage). In cases where the reduction of soil evaporation alone is larger than the increased plant transpiration, the resulting increase in soil moisture may even lead to an overall increase in total runoff (sum of all surface and subsurface runoff components) (Fig. 3A).

Steiner (1989) conducted field and laboratory trials and reported functions for wheat and sorghum to estimate changes in evaporation based on the residue amount. These functions were used to evaluate the evaporative reduction from a layer of residues using the bare soil simulations. We find that an application of 75 g C m^{-2} yr^{-1} of residues reduces evaporation by -18.2% (5^{th}, 95^{th} percentile: -34.0%, -2.1%) (Appendix – Fig. 6B), 150 g C m^{-2} yr^{-1} by -40.3% (5^{th}, 95^{th} percentile: -55.6%, -9.0%) (Appendix – Fig. 6C) and 300g C m^{-2} yr^{-1} by -62.2% (5^{th}, 95th percentile: -73.4%, -34.4%) (Appendix – Fig. 6D). Using the functions provided by Steiner (1989), residue amounts can be translated into a reduction of evaporation by -36.3% for wheat and -16.5% for sorghum for the low application rates, by -50.2% for wheat and -30.7% for sorghum for the medium application rates and by -64.0% for wheat and by -44.9% for sorghum for the high application rates, respectively (Table 4). These values for evaporation reduction from prescribed residue loads are well reproduced by the model. Overall, soil evaporation in the first 3 years of MS duration in the NT_R scenario is reduced by -28.4% (5th, 95th percentile: -49.0%, -11.3%) compared to the T_R (Fig. 3B).

[Fig. 3]

5.4 N_2O fluxes

Overall, switchingSwitching from tillage to no-till management with additional residue inputleaving residues on the fields (NT_R vs. T_R) increases N_2O emissions by +7.a median of +19.9% (5th, 95th percentile: -5% (5th, 95th percentile: -6.7%, +68.9.8%, +341.0%) (Appendix – Fig. 7A5A). The strongest increase is found in the warm temperate zone where the average increase is 11.3+25.1% (5th, 95th percentile: +0.7%, +75.75.9%, +195.3%) (Appendix – Fig. 7B5B). The lowest increase is found in the tropical zone +2.912.6% (5th, 95th percentile: -8.5%, +43.39.1%, +67.7%) (Appendix – Fig. 7C5C).

The increase in N_2O emissions after switching to no-till is in agreement with several literature studies (Linn and Doran, 1984; Mei et al., 2018; van Kessel et al., 2013; Zhao et al., 2016) (Table 43). Mei et al. (2018) reports an overall increase of +17.3% (95th CI: +4.6%, +31.1%), which is higher than our values, but both ranges mostly overlap. However, although the overall effect is in agreement with Mei et al. (2018), the spatialin agreement with our median estimate. However, the regional patterns over the different climatic regimes are in less agreement. WeLPJmL simulations strongly underestimate the increase in N_2O emissions in the tropical zone compared to Mei et al. (2018), who reported an increase of +74.1% (95th CI: +34.8%, +119.9%). Moreover, the N_2O emissions in arid regions after switching to no-till are underestimated (Appendix – Fig. 8B), but still within the range, compared to van Kessel et al. (2013), who reported an increase of +35.0% (95th CI: +7.5%,+69%). In the cold temperate (Appendix – Fig. 7D) and humid zones (Appendix – Fig. 8A) we slightly overestimate on average, and the 95th percentile of our ranges is relatively high compared to , whereas simulations overestimate the response in cool temperate and humid zones and to some extent in the warm temperate zone (Table 3).

In general, N_2O emissions are formed in two separate processes: nitrification and denitrification. The increase in N_2O emissions after adapting to NT_R is mainly resulting from denitrification in our simulations (+55.6%, Fig. 5A). This increase is visible in most of the regions. The N_2O emissions resulting from nitrification decrease mostly (median of -7.2%, Fig. 5B) but tends to increase in dry areas. The increase in denitrification and decrease in nitrification, results in a decrease in NO_3^- (median of -26.8%), which appears to be stronger in the tropical areas as well (Fig. 5D). The transformation of mineral N to N_2O is not only affected by the nitrification and denitrification rates, but also by substrate availability (NH_4^+ and NO_3^- respectively). These in turn are affected by nitrification and denitrification rates, but also by other processes, such as plant uptake and leaching. In the Sahel zone for example, denitrification decreases and nitrification increases, but NO_3^- stocks decline, because leaching increase more strongly (Appendix 6).

In LPJmL, denitrification and nitrification rates are mainly driven by soil moisture and to a lesser extent by soil temperature, soil C (denitrification) and soil pH (nitrification). A strong increase in annually averaged soil moisture can be observed after adapting NT_R (median of +18.8%, Fig. 5C). Denitrification, as an anoxic process, increases non-linearly beyond a soil moisture threshold (von Bloh et al. 2018), whereas there is an optimum soil moisture for nitrification, which is reduced at low and high soil moisture content. In wet regions, as in the tropical and humid areas, nitrification is thus reduced by no-till practices whereas it increases in dryer regions. The increase in soil moisture under NT_R is caused by higher water infiltration rates and reduced soil evaporation (see section ~~Mei et al. (2018) (average: -1.7% and 95th CI: -10.5%, +8.4%) and van Kessel et al. (2013) (average: -1.~~5.4). Also, no-till practices tend to increase bulk density and thus higher relative soil moisture contents (Fig. 1) also affecting nitrification and denitrification rates and therefore N_2O emissions (van Kessel et al., 2013; Linn and Doran, 1984). ~~% and 95th CI: -11.6%, +11.1%). This is also the case for the warm temperate zone, though the median and average increase is in agreement with Mei et al. (2018), who report an increase of +17% (95th CI: +6.5%, +29.9%) (Table 4).~~

~~The increase in N_2O emissions under NT_R can be explained by two mechanisms. Firstly, under no-till with residues, more water can infiltrate into the soil and less water is lost through evaporation. This can cause anaerobic conditions, which trigger N_2O emissions from denitrification. Secondly, no-till tends to increase bulk density and moisture content, which results additionally in a larger water filled pore space (Fig. 1) which can increase the denitrification rate,~~Empirical evidence shows that the introduction of no-till practices~~ and therefore N_2O emissions (van Kessel et al., 2013; Linn and Doran, 1984).~~

~~However, the impact of no-till~~ on N_2O emissions ~~has been variable with~~can cause both increases and decreases in N_2O emissions ~~reported~~ (van Kessel et al., 2013). This variation in response is not surprising, as tillage affects several biophysical factors that influence N_2O emissions (Fig. 1) in possibly contrasting manners (van Kessel et al., 2013; Snyder et al., 2009). For instance~~,~~ no-till can lower soil temperature exchange between soil and atmosphere, through the presence of litter residues, which can reduce N_2O emissions (~~Six~~Enrique et al~~., 2004). Moreover, under T_R, more C (from residues) is incorporated into the soil, which leads to more substrate for N_2O emissions.~~. 1999). Reduced N_2O emissions under no-till compared to ~~the~~ tillage MS can also be observed in the model results, for instance in ~~North-East India, South-East Asia~~Northern Europe and areas in Brazil (Appendix ~~–Fig. 7A~~5A).

~~Various studies where field experiments~~As several biophysical factors are ~~conducted report high uncertainties associated with the estimation of~~affected, N_2O emissions~~, due to~~ are characterized by significant spatial and temporal variability~~,~~. As a result, the estimation of N_2O emissions are accompanied with high uncertainties (Butterbach-Bahl et al., 2013), which hampers the evaluation of the model results (Chatskikh et al., 2008; Mangalassery et al., 2015). ~~Moreover, the relevant processes behind N_2O emissions are still not fully understood (Lugato et al., 2018).~~

The deviations from the model results compared to the meta-analyses especially for specific climatic regimes (i.e. tropical- and cool temperate) ~~cannot be explained other than~~ require further investigations and verification, including model simulations for specific sites at which experiments have been conducted. The sensitivity of N_2O emissions ~~are sensitive to subtle changes in~~highlights the importance of correctly simulating soil moisture~~, forms of reactive N and timing, which renders all comparisons to patchy data difficult. Additional model evaluation~~. However, simulating soil moisture is ~~needed~~subject to strong feedback with vegetation performance and comes with uncertainties, as addressed by e.g.~~, conducting sensitivity analysis of specific inputs (e.g., soil type-, N-~~

fertilizer). Seneviratne et al. (2010). The effects of different management settings (as conducted here), on N_2O emissions and soil moisture requires therefore further analyses, ideally in different climate regimes for testing the model behavior. , soil types and in combination with other management settings (e.g. N-fertilizers). We expect that further studies using this tillage implementation in LPJmL will further increase understanding of management effects on soil nitrogen dynamics. The great diversity in observed responses in N_2O emissions to management options (Mei et al. 2018) renders modeling these effects as challenging, but we trust that the ability of LPJmL5.0-tillage to represent the different components can also help to better understand their interaction under different environmental conditions.

-*[Fig. 5]*

[Table 43]

5.5.6 General discussion

The implementation of tillage into the global ecosystem model LPJmL opens opportunities to assess the effects of different tillage and no-till practices on agricultural productivity and its environmental impacts, such as nutrient cycles, water consumption, GHG emissions and C sequestration. and is a general model improvement to the previous version of LPJmL (von Bloh et al., 2018). The implementation involved 1) the introduction of a surface litter pool that is incorporated into the soil column at tillage events and the subsequent effects on soil evaporation and infiltration, 2) dynamicdynamically accounting for *SOM*SOM content in computing soil hydraulic properties, and 3) simulating tillage effects on physicalbulk density and the subsequent effects of changed soil water properties. and all water-dependent processes (Fig. 1).

In general, a global model implementation on tillage practices is difficult to evaluate, as effects are reported often to be quite variable, depending on soil conditions. We find that the model results for NT_R compared to T_R are in agreement with literature for C stocks and fluxes, water fluxes and to a lesser extent N_2O emissions when compared to reported impact ranges in meta-analyses. Effects can also change over time so that a comparison needs to also consider the timing, history and duration of management changes. For C, e.g., we see that NT_R has a positive effect on *SOM* and reduces CO_2 emissions the first years after adapting to NT_R, but increases CO_2 emissions in the mid- and long-term owing to a larger accumulation of *SOM*.

In this study, model results were evaluated with data ranges as compiled bylocal soil and climatic conditions. The model results were evaluated with data compiled from meta-analyses, which implies several limitations. Due to the limited amount of available meta-analyses, not all fluxes and stocks could be evaluated within the different management scenarios. Especially for testing residue-only effects, it would have been good to have additional studies to analyzeFor the effects of $Cover_{surf}$, which has a strong influenceevaluation we focused on water productivity, soil and litter C stocks and fluxes (e.g., evaporation) and thus affects various other relevant, water fluxes that are sensitive to soil moisture as well. Also, theand N_2O dynamics. The sample size in some of these meta-analyses was sometimes low, which may result in biases if not all conditions (e.g., a representative set of climate and soil combinations) were was tested, and it remains unclear how these can be best compared to. Clearly a full samplingcomparison of a small sample size to simulations of the global cropland as in the modeling resultsis challenging. Nevertheless, the meta-analyses gave the best overview of the overall effects of tillage practices that have been reported for various individual experiments.

When applying We find that the model results for NT_R compared to T_R are generally in agreement with literature with regard to magnitude and direction of the effects on C stocks and fluxes. Despite some disagreement between reported ranges in effects and model simulations, we find that the diversity in modeled responses across environmental gradients is an asset of the model. The underlying model mechanisms as the initial decrease in CO_2 emissions after introduction of no-till practices that can be maintained for longer time periods in moist regions but is inverted in dry regions due to the feedback of higher water availability on plant productivity and reduced turnover times and generally increasing soil carbon stocks (Fig. 3) are plausible and in line with general process understanding. Certainly, the interaction of the different processes may not be captured correctly and further research on this is needed. We trust that this model implementation, representing this complexity allows for further research in this direction. For water fluxes the model seems to overestimate the effect of surface residue cover on evaporation for high surface cover, but the evaluation is also constrained by the small number of suitable field studies. Effects can also change over time so that a comparison needs to consider the timing, history and duration of management changes and specific local climatic and soil conditions. The overall effect of NT_R compared to T_R on N_2O emissions are in agreement with literature as well. However, the regional patterns over the different climatic regimes are in less agreement. N_2O emissions are highly variable in space in time and are very sensitive to soil water dynamics (Butterbach-Bahl et al., 2013). The simulation of soil water dynamics differs per soil type as the calculation of the hydraulic parameters is texture specific. Moreover, these parameters are now changed after a tillage event. The effects of tillage on N_2O emissions, as well as other processes that are driven by soil water (e.g. CO_2, water dynamics) can therefore be different per soil type. The soil specific effects of tillage on N_2O and CO_2 emissions was already studied by Abdalla et al. (2016) and Mei et al. (2018). Abdalla et al. (2016) found that differences in CO_2 emissions between tilled and untilled soils are largest in sandy soils (+29%), whereas the differences in clayey soils are much smaller (+12%). Mei et al. , it(2018) found that clay content <20% significantly increases N_2O emissions (+42.9%) after adapting to conservation tillage, whereas this effect for clay content >20% is smaller (+2.9%). These studies show that soil type specific tillage effects on several processes can be of importance and should be investigated in more detail in future studies. The interaction of all relevant processes is complex, as seen in Figure 1, which can also lead to high uncertainties in the model. Again, we think that this model implementation captures substantial aspects of this complexity and thus lays the foundation for further research. .

It is important to be awarenote that not all processes related to tillage and no-till are taken into account. in the current model implementation. For instance, NT_R can improve soil structure (e.g., aggregates) due to increased faunal activity (Martins et al., 2009), which can result in a decrease in BD. Although tillage hascan have several advantages for famers (the farmer, e.g. residue incorporation and topsoil loosening),, it can also have several disadvantages as well. For instance, tillage can result incause compaction of the subsoil, (Bertolino et al., 2010), which result in an increase in BD (Podder et al., 2012). Moreover, the absence of a residue layer can drive soil crusting which affects the infiltration of soil water. However,) and creates a barrier for percolating water, leading to ponding and an oversaturated topsoil. Strudley et al. (2008) however observed mixeddiverging effects of tillage and no-till on hydraulic properties (, such as BD). Nevertheless, they motivate more fruitful investigations into, Ks and whc for different locations. They argue that affected processes of agricultural management practices and their interacting influenceshave complex coupled effects on soil hydraulic properties., as well as that variations in space and time often lead to higher differences than the measured differences between the management treatments. They also argue that characteristics of soil type and climate are unique for each location, which cannot simply be transferred from one field location to another. A process-based representation of tillage effects as in this extension of LPJmL allows for further studying management effects across diverse environmental conditions, but also to refine model parameters and implementations where experimental evidence suggests disagreement.

One of the primary reasons for tillage, weed control, is also not accounted for in ~~LPJmL~~ LPJmL5.0-tillage or ~~most~~in other ecosystem models. As such, different tillage and residue management strategies can only be assessed with respect to their biogeochemical effects, but only partly with respect to their effects on productivity and not with respect to some environmental effects (e.g. pesticide use). Our model simulations show that crop yields increase under no-till practices in dry areas but decrease in wetter regions (Fig. 2). However, the median response is positive, which may be in part because the water saving effects from increased soil cover with residues are overestimated or because detrimental effects, such as competition with weeds, are not accounted for.

The included processes now allow us to analyze long term feedbacks of productivity on soil and litter C stocks and N dynamics. Nevertheless the results need to be interpreted carefully, due to the capacity of the model and implemented processes. We also find that the modeled impacts of tillage are very diverse in space as a result of different framing conditions (soil, climate, management) and feedback mechanisms, such as improved productivity in dry areas if residue cover increases plant available water. The process-based representation in the LPJmL5.0-tillage of tillage and residue management and the effects on water fluxes such as evaporation and infiltration at the global scale is unique in the context of global biophysical models (e.g. Friend et al. 2014, (LeQuéré et al., 2018). Future research on improved parameterization and the implementation of more detailed representation of tillage processes and the effects on soil water processes, changes in porosity and subsoil compaction, effects on biodiversity and on soil N dynamics is needed in order to better assess the impacts of tillage and residue management at the global scale. Data availability, the spatial resolution needed to resolve processes, such as erosion, and model structure need to be considered in further model development (Lutz et al. 2019). As such, some processes, such as a detailed representation of soil crusting processes, may remain out of reach for global-scale modeling.

6 Conclusion

We described the implementation of tillage related ~~practices in~~processes into the global ecosystem model ~~LPJmL 5~~LPJmL5.0-tillage. The extended model was tested under different management scenarios and evaluated by comparing to reported impact ranges from meta-analyses on C, water and N dynamics as well as on crop yields.

~~We were~~We find that mostly arid regions benefit from a no-till management with leaving residues on the field, due to the water saving effects of surface litter. We are able to broadly reproduce reported tillage effects on global stocks and fluxes, as well as regional patterns of these changes, with ~~LPJmL 5~~LPJmL5.0-tillage but deviations in N-fluxes need to be further examined. Not all effects of tillage, including one of its primary reasons, weed control, could be accounted for in this implementation. Uncertainties mainly arise because of the multiple feedback mechanisms affecting the overall response to tillage, especially as most processes are affected by soil moisture. The processes and feedbacks presented in this implementation are complex and evaluation of effects is often limited in the availability of reference data. Nonetheless, the implementation of more detailed tillage-related mechanics into global ecosystem model LPJmL improves our ability to represent different agricultural systems and to understand management options for climate change adaptation, agricultural mitigation of GHG emissions and sustainable intensification. We trust that this model implementation and the publication of the underlying source code promote research on the role of tillage for agricultural production, its environmental impact and global biogeochemical cycles.

Code and data availability. The source code and data is available upon request from the main author for the review process and for selected collaborative projects. The source code will be generally available after final publication of this paper and a DOI for access will be provided.

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Table 1: LPJmL simulation settings and tillage parameters used in the stylized simulations for model evaluation.

Scenario	*Simulation abbreviation*	*Retained residue fraction on field*	*Tillage efficiency (TLFrac)*	*Mixing efficiency of tillage (mE)*	*Litter cover[+] (%)*	*Litter amount (dry matter g m^2)*
Tillage + residues on 100% scaled cropland	T_R	1	0.95	0.9	variable*	variable*
Tillage + no residues on 100% scaled cropland	T_NR	0.1	0.95	0.9	variable*	variable*
No-till + residues on 100% scaled cropland	NT_R	1	0	0	variable*	variable*
No-till + no residues on 100% scaled cropland	NT_NR	0.1	0	0	variable*	variable*
No-till + no residues on bare soil	NT_NR_bs	0	0	0	0	0
No-till + residues on bare soil (1)	NT_R_bs1	1	0	0	10	17
No-till + residues on bare soil (2)	NT_R_bs2	1	0	0	30	60
No-till + residues on bare soil (3)	NT_R_bs3	1	0	0	50	117
No-till + residues on bare soil (4)	NT_R_bs4	1	0	0	70	202
No-till + residues on bare soil (5)	NT_R_bs5	1	0	0	90	383

~~Table 2: LPJmL simulation settings for the evaluation.~~

Scenario	Simulation abbreviation	Retained residue fraction on field	Tillage efficiency (TL_{Frac})	Mixing efficiency of tillage (mE)
Tillage + residues	T-R	1.0	0.95	0.90
Tillage + no residues	T-NR	0.1	0.95	0.90
No tillage + residues	NT-R	1.0	0	0
No tillage + no residues	NT-NR	0.1	0	0

Table 3 [+] Litter cover is calculated following Gregory (1982).
*Litter amounts and litter cover are modeled internally.

Table 2: Percentage values for each soil textural class of silt, sand and clay content used in LPJmL and correspondent hydraulic parameters before and after tillage with 0% and 8% SOM using the Saxton and Rawls (2006) pedotransfer function.

				pre-tillage, 0% SOM**				pre-tillage, 8% SOM				after tillage[++], 0% SOM				after tillage[++], 8% SOM			
Soil class	Silt (%)	Sand (%)	Clay (%)	whc[++]	W_{sat}	W_{fc}	Ks	whc	W_{sat}	W_{fc}	Ks	whc	W_{sat}	W_{fc}	Ks	whc	W_{sat}	W_{fc}	Ks
Sand	5	92	3	0.04	0.42	0.05	152.05	0.09	0.71	0.19	361.98	0.08	0.59	0.09	343.67	0.14	0.80	0.21	498.92
Loamy sand	12	82	6	0.06	0.40	0.09	83.23	0.12	0.70	0.23	244.20	0.10	0.58	0.13	230.13	0.17	0.79	0.25	360.89
Sandy loam	32	58	10	0.12	0.40	0.17	32.03	0.18	0.70	0.31	152.75	0.15	0.58	0.21	125.75	0.23	0.79	0.33	239.93
Loam	39	43	18	0.15	0.41	0.26	10.69	0.21	0.69	0.37	80.46	0.19	0.59	0.30	64.76	0.25	0.78	0.39	143.99
Silty loam	70	17	13	0.22	0.42	0.31	5.49	0.29	0.75	0.42	99.77	0.26	0.59	0.34	48.23	0.32	0.83	0.44	155.38
Sandy clay loam	15	58	27	0.12	0.42	0.28	6.60	0.17	0.63	0.38	36.33	0.16	0.59	0.32	48.79	0.21	0.74	0.40	87.40
Clay loam	34	32	34	0.17	0.47	0.38	2.29	0.20	0.65	0.43	24.96	0.21	0.63	0.41	26.22	0.23	0.75	0.45	63.73
Silty clay loam	56	10	34	0.21	0.50	0.42	1.93	0.23	0.69	0.45	34.54	0.24	0.65	0.45	22.45	0.25	0.78	0.47	73.85
Sandy clay	6	52	42	0.15	0.47	0.40	0.72	0.16	0.58	0.44	5.64	0.18	0.63	0.44	16.73	0.20	0.70	0.47	29.30
Silty clay loam	47	6	47	0.20	0.56	0.48	1.64	0.18	0.65	0.46	18.69	0.23	0.69	0.50	16.67	0.20	0.76	0.48	50.99
Clay	20	22	58	0.19	0.58	0.53	0.39	0.14	0.58	0.48	2.87	0.21	0.71	0.55	8.62	0.16	0.71	0.50	20.03
Rock*	0	99	1	0.00	0.01	0.01	0.10	0.00	0.01	0.01	0.10	0.00	0.01	0.01	0.10	0.00	0.01	0.01	0.10

*Soil class rock is not affected by SOM changes and tillage practices

**For SOM we only consider the C part in SOM in gC/m^2

[+]Tillage with a *mE* of 0.9 for conventional tillage

[++]whc is calculated as: whc = W_{fc} - W_{pwp} in all cases

Table 3: Comparison of simulated model output and literature values from meta-analysis.

Variable/Scenario	Soil depth (m)	# of paired treatments	Literature mean (95% interval)	Time horizon (years)	Modeled response (median %)	Modeled response (5% and 95% percentile)	Reference
notill residue - till residue							
SOM (0.3m)	0-0.3	101	+5.0 (+1.0, +9.2)*‡	10§	+4.6	+1.0, +12.9	Abdalla et al., 2016
CO2		113	-23.0 (-35.0, -13.8)*	**	-11.8	-24.5, +2.1	Abdalla et al., 2016
N2O		98	+17.3 (+4.6, +31.1)*	**	+19.9	-5.8, +341.0	Mei et al., 2018
N2O (tropical)		123	+74.1 (+34.8, +119.9)†‡	**	+12.6	-9.1, +67.7	Mei et al., 2018
N2O (warm temperate)		62	+17.0 (+6.5, +29.9)†‡	**	+25.1	+5.9, +195.3	Mei et al., 2018
N2O (cool temperate)		27	-1.7 (-10.5, +8.4)†‡	**	+23.6	-2.9, +783.1	Mei et al., 2018
N2O (arid)		56	+35.0 (+7.5, +69)*	**	+22.5	-1.8, +533.1	Kessel et al., 2013
N2O (humid)		183	-1.5 (-11.6, +11.1)*	**	+16.7	-15.6, +58.6	Kessel et al., 2013
Yield (wheat)		47	-2.6 (-8.2, +3.8)*	10§	+1.7	-24.4, +54.8	Pittelkow et al. 2015b
Yield (maize)		64	-7.6 (-10.1, -4.3)*	10§	+1.0	-34.2, +55.6	Pittelkow et al. 2015b
Yield (rapeseed)		10	+0.7 (-2.8, +4.1)*	10§	+2.4	-34.8, +61.0	Pittelkow et al. 2015b
till noresidue - notill noresidue							
SOM (0.3m)	0-0.3	46	-12.0 (-15.3, -5.1)*	20§	-17.6	-43.0, -0.4	Abdalla et al., 2016
CO2		46	+18.0 (+9.4, +27.3)*	20§	+20.9	-1.2, +125.8	Abdalla et al., 2016
Yield (wheat) B		8	+2.7 (-6.3, +12.7)*	10§	-4.2	-14.1, +10.4	Pittelkow at al. 2015b
Yield (maize) B		12	-25.4 (-14.7, -34.1)*	10§	-2.8	-22.5, +31.3	Pittelkow et al. 2015b
till noresidues - till residue							
N2O		105	+1.3 (-5.4, +8.2)*‡	**	-9.4	-21.8, +3.9	Mei et al., 2018

*estimated from graph
**Time horizon of the study is unclear in the meta-analysis. The average over the first three years of model results is taken.

† includes conservation till

†† at least 30% on soil
‡ Residue management for conventional till unsure
§ Time horizon not explicitly mentioned by author

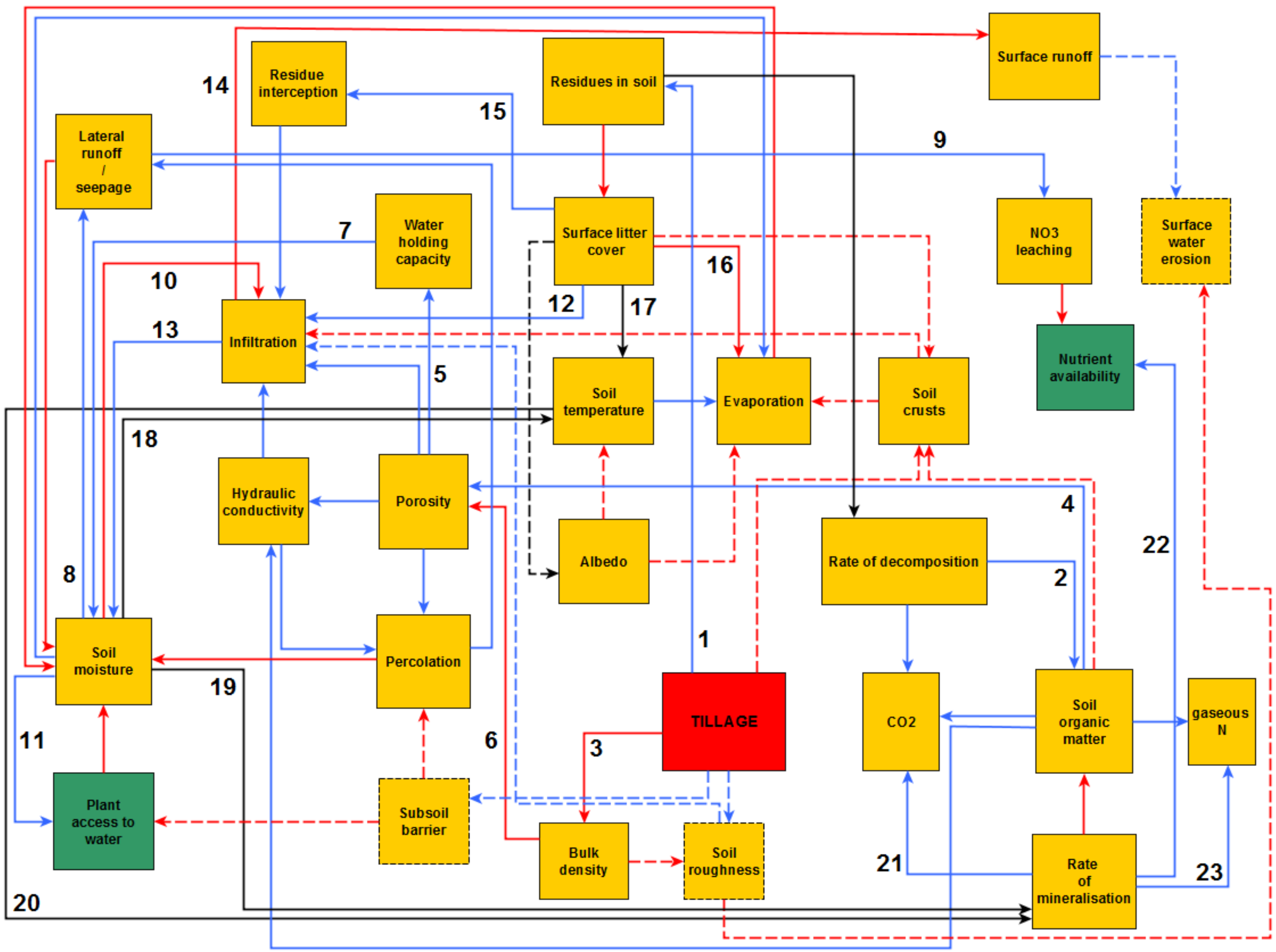
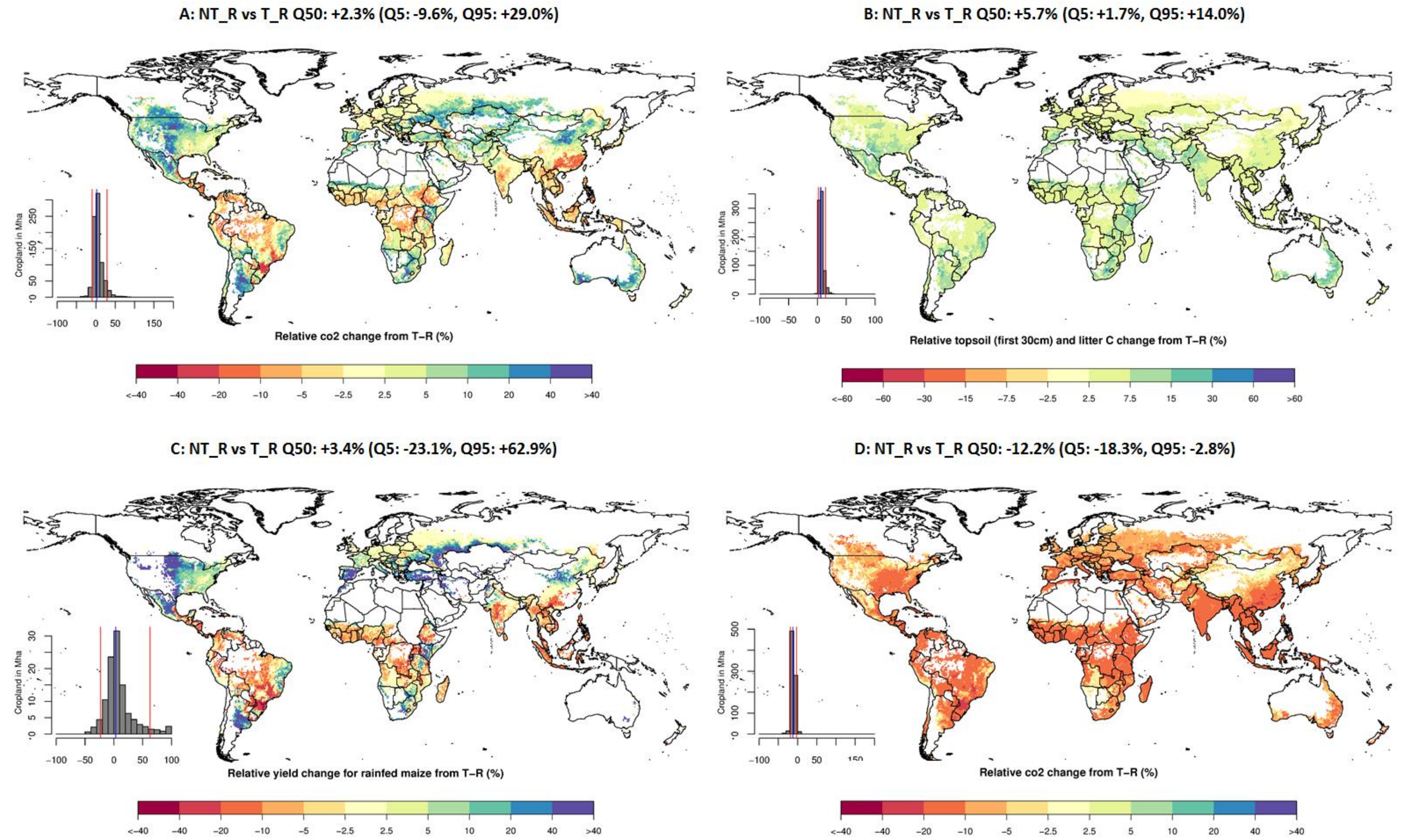
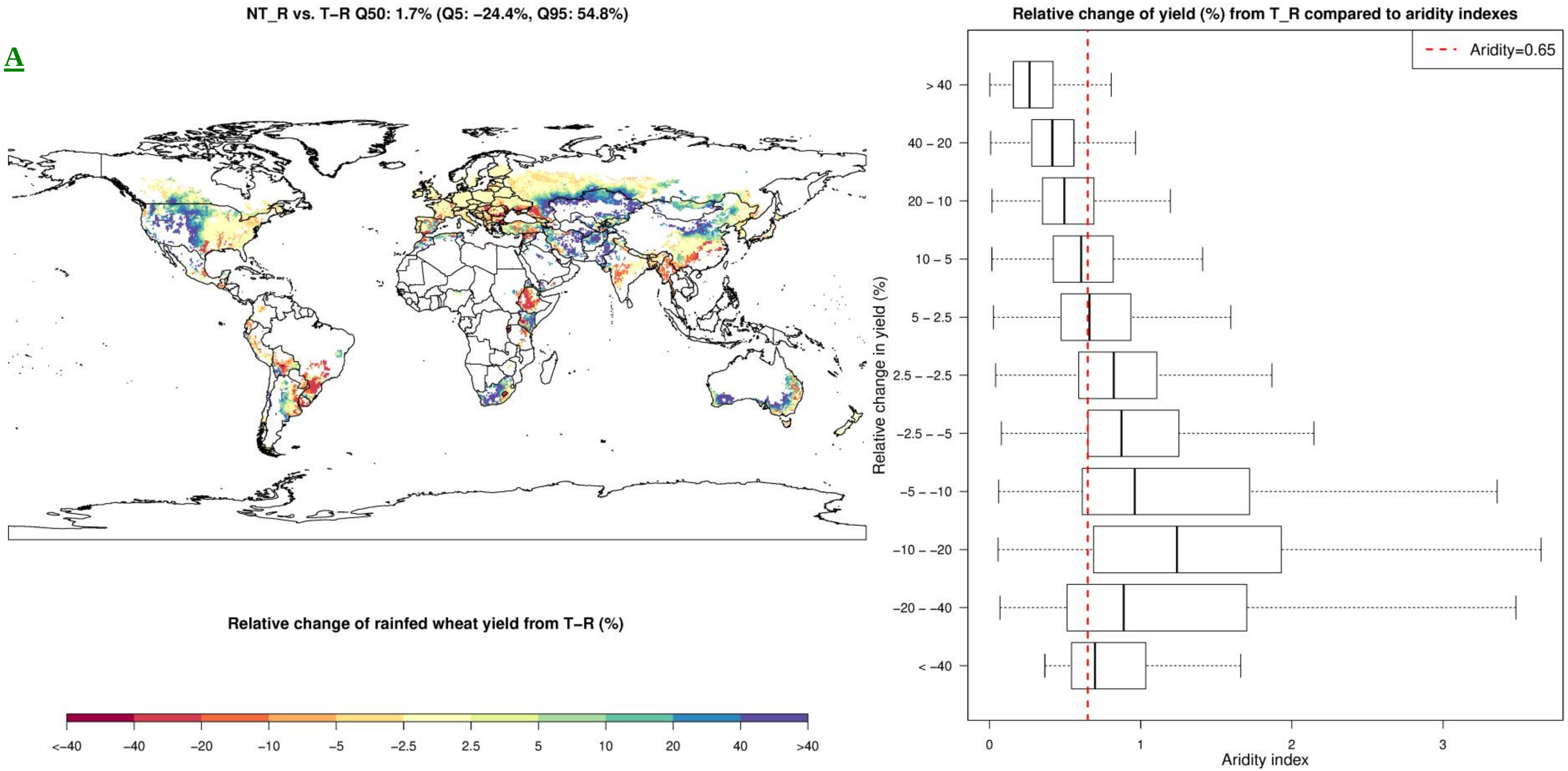


Figure 1: Flow chart diagram of feedback processes caused by tillage, which are considered (~~dashed~~solid lines) and not considered (dashed lines) in ~~LPJmL.~~this implementation in LPJmL5.0-tillage. Blue lines highlight positive feedbacks, red negative and black are ambiguous feedbacks. The numbers in the figure indicate the processes described in chapter 2.


A: NT_R vs T_R Q50: +2.3% (Q5: -9.6%, Q95: +29.0%)
Cropland in Mha
Relative co2 change from T−R (%)
<−40 −40 −20 −10 −5 −2.5 2.5 5 10 20 40 >40
B: NT_R vs T_R Q50: +5.7% (Q5: +1.7%, Q95: +14.0%)
Cropland in Mha
Relative topsoil (first 30cm) and litter C change from T−R (%)
<−60 −60 −30 −15 −7.5 −2.5 2.5 7.5 15 30 60 >60
C: NT_R vs T_R Q50: +3.4% (Q5: -23.1%, Q95: +62.9%)
Cropland in Mha
Relative yield change for rainfed maize from T−R (%)
<−40 −40 −20 −10 −5 −2.5 2.5 5 10 20 40 >40
D: NT_R vs T_R Q50: -12.2% (Q5: -18.3%, Q95: -2.8%)
Cropland in Mha
Relative co2 change from T−R (%)
<−40 −40 −20 −10 −5 −2.5 2.5 5 10 20 40 >40

~~Fig.~~

A


NT_R vs. T–R Q50: 1.7% (Q5: –24.4%, Q95: 54.8%)
Relative change of rainfed wheat yield from T–R (%)
<–40
–40
–20
–10
–5
–2.5
2.5
5
10
20
40
>40
Relative change of yield (%) from T_R compared to aridity indexes
Aridity=0.65
> 40
40 – 20
20 – 10
10 – 5
5 – 2.5
2.5 – –2.5
–2.5 – –5
–5 – –10
–10 – –20
–20 – –40
< –40
Relative change in yield (%)
0
1
2
3
Aridity index

B

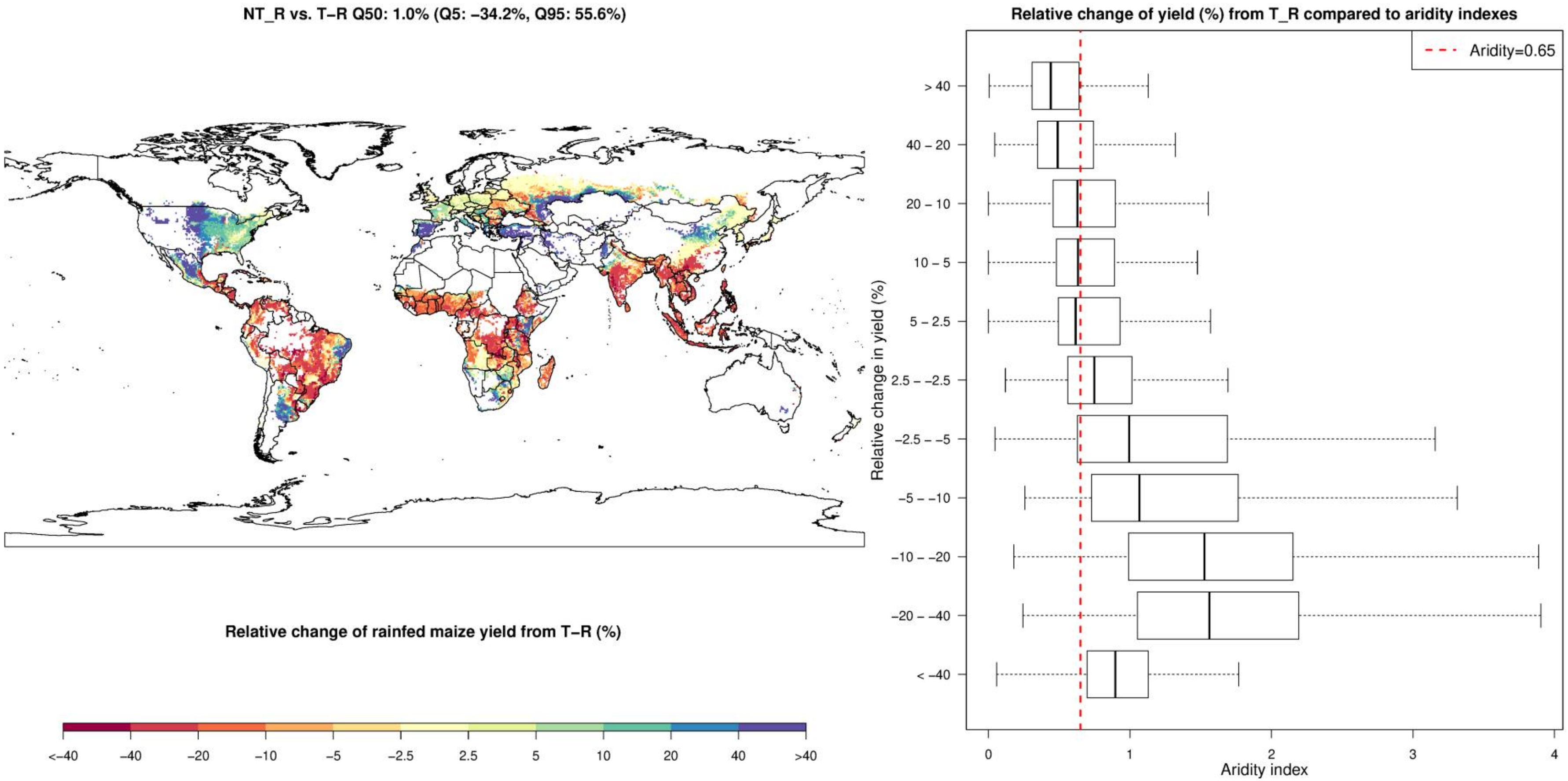
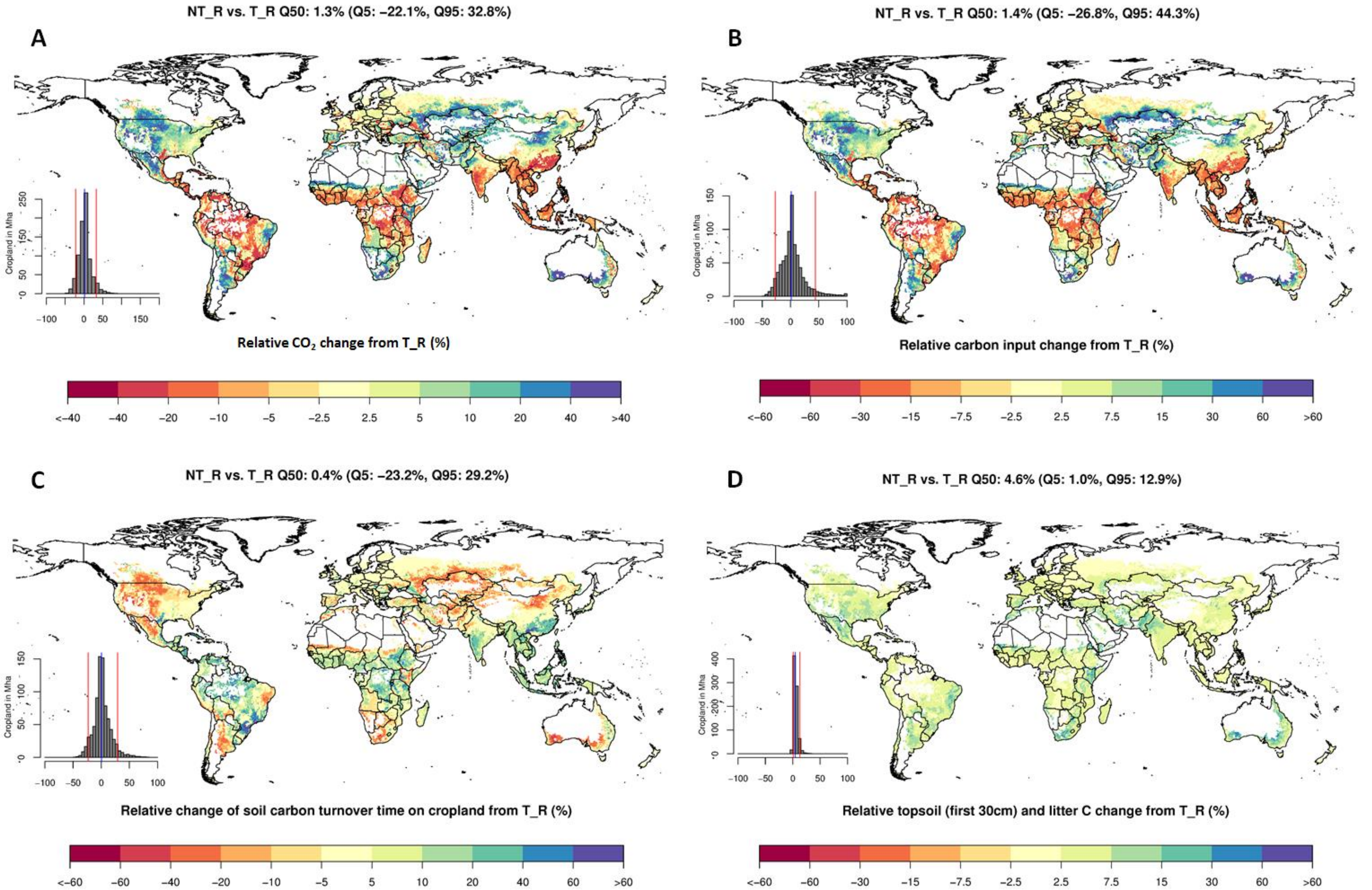


Figure 2: Relative yield changes for rain-fed wheat (A) and rain-fed maize (B) compared to aridity indexes after ten years NT_R vs. T_R.



A
NT_R vs. T_R Q50: 1.3% (Q5: −22.1%, Q95: 32.8%)
Cropland in Mha
0 50 150 250
−100 0 50 150
Relative CO2 change from T_R (%)
<−40 −40 −20 −10 −5 −2.5 2.5 5 10 20 40 >40
B
NT_R vs. T_R Q50: 1.4% (Q5: −26.8%, Q95: 44.3%)
Cropland in Mha
0 50 100 150
−100 −50 0 50 100
Relative carbon input change from T_R (%)
<−60 −60 −30 −15 −7.5 −2.5 2.5 7.5 15 30 60 >60
C
NT_R vs. T_R Q50: 0.4% (Q5: −23.2%, Q95: 29.2%)
Cropland in Mha
0 50 100 150
−100 −50 0 50 100
Relative change of soil carbon turnover time on cropland from T_R (%)
<−60 −60 −40 −20 −10 −5 5 10 20 40 60 >60
D
NT_R vs. T_R Q50: 4.6% (Q5: 1.0%, Q95: 12.9%)
Cropland in Mha
0 100 200 300 400
−100 −50 0 50 100
Relative topsoil (first 30cm) and litter C change from T_R (%)
<−60 −60 −30 −15 −7.5 −2.5 2.5 7.5 15 30 60 >60

Figure 3: Relative C dynamics comparingfor NT_R vs. T_R —Relativecomparison after ten years of simulation experiment (average of year 9-11) for relative CO_2 change after ten years (A(A), relative C input change (B), relative change of soil C turnover time (C), relative topsoil and litter C change after ten years (B), relative yield change for rain-fed maize after ten years (C), relative CO_2 change after three years (D).

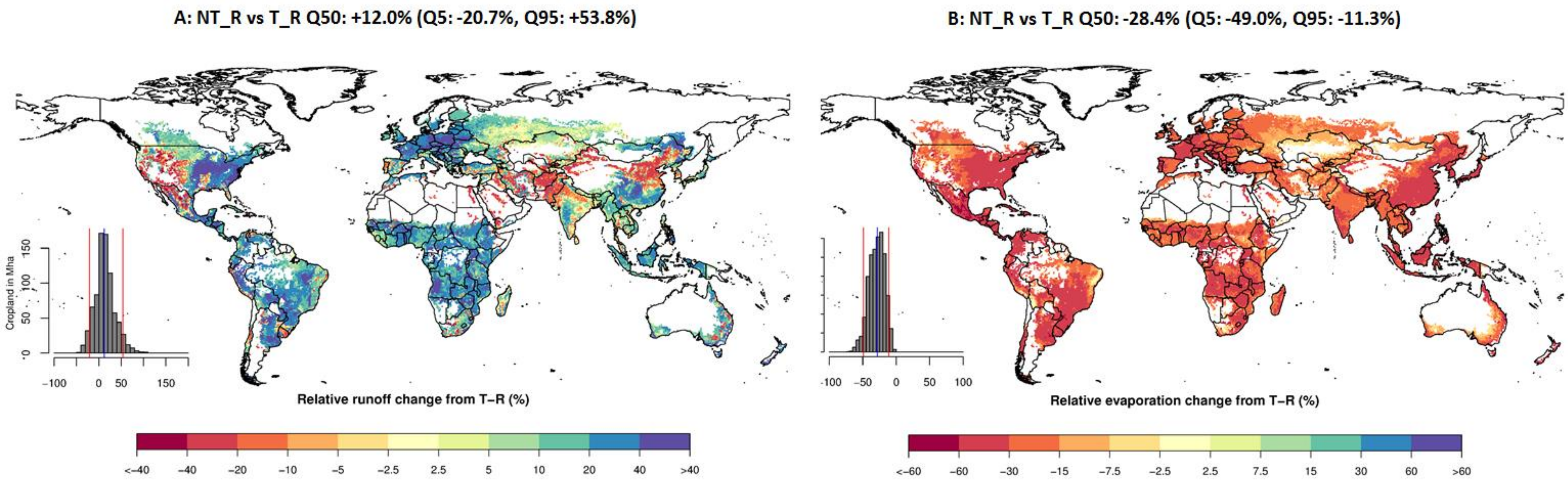
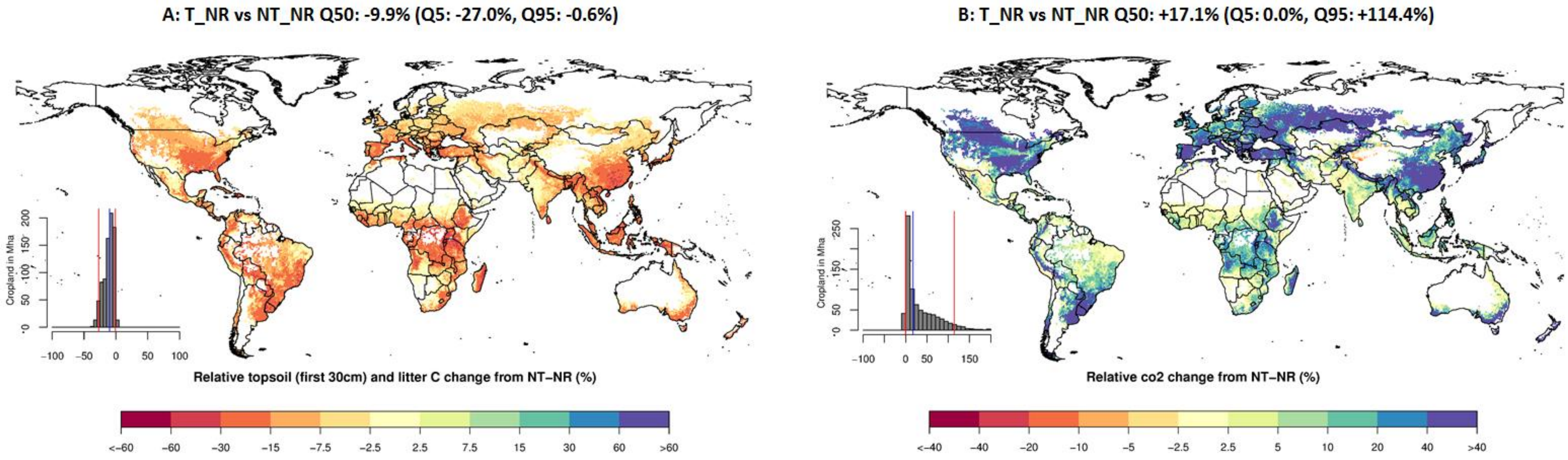
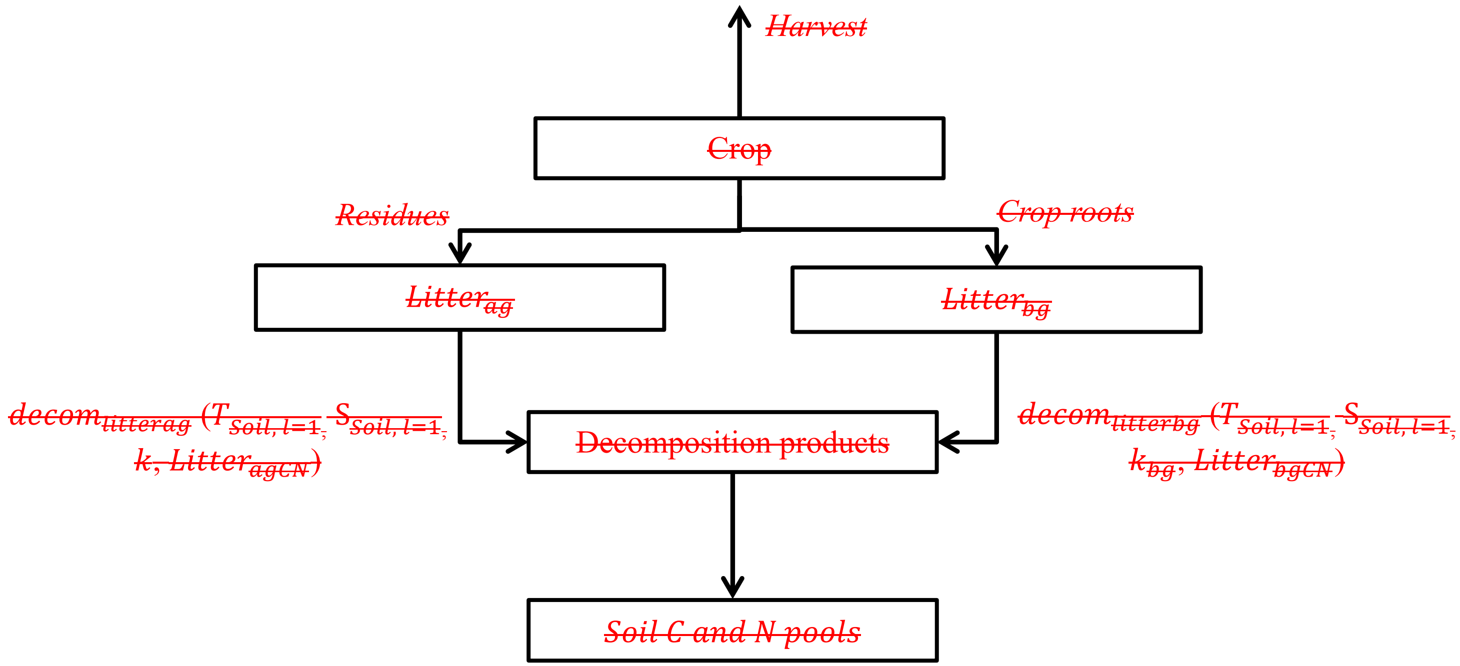


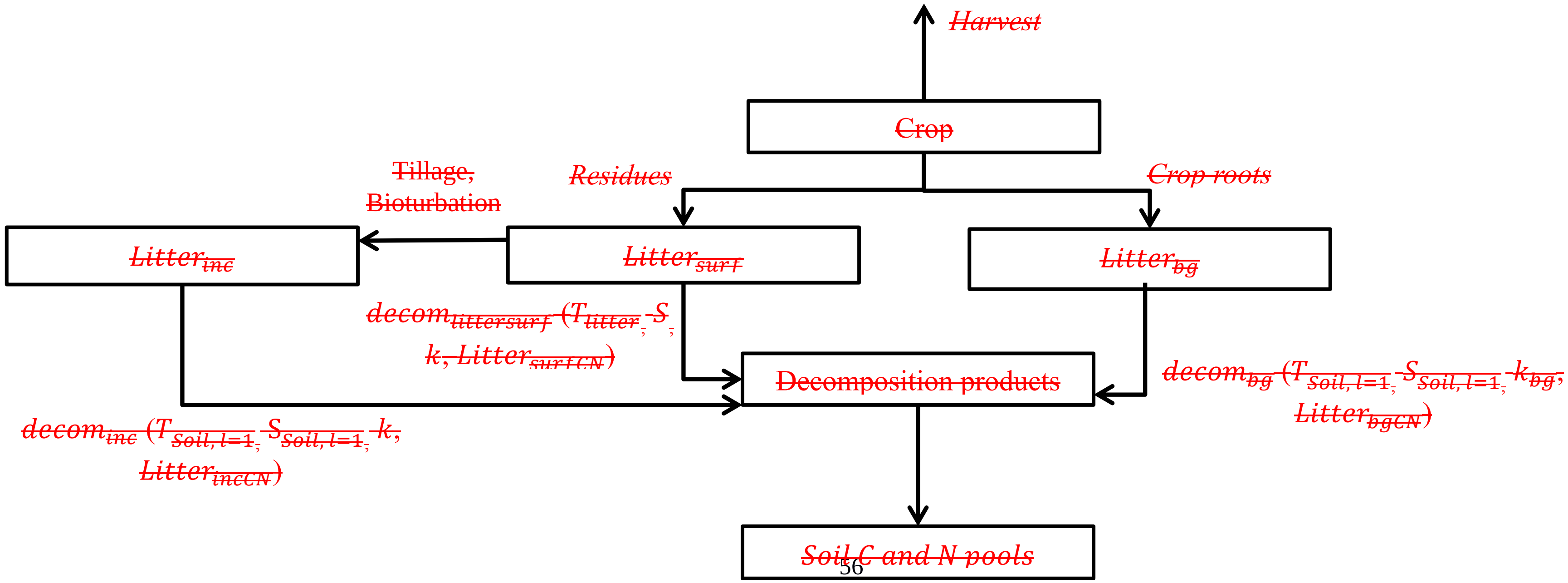
Fig. 3: Relative changes in runoff (A) and evaporation (B) comparing NT_R vs. T_R for the average of the first three years after implementation.



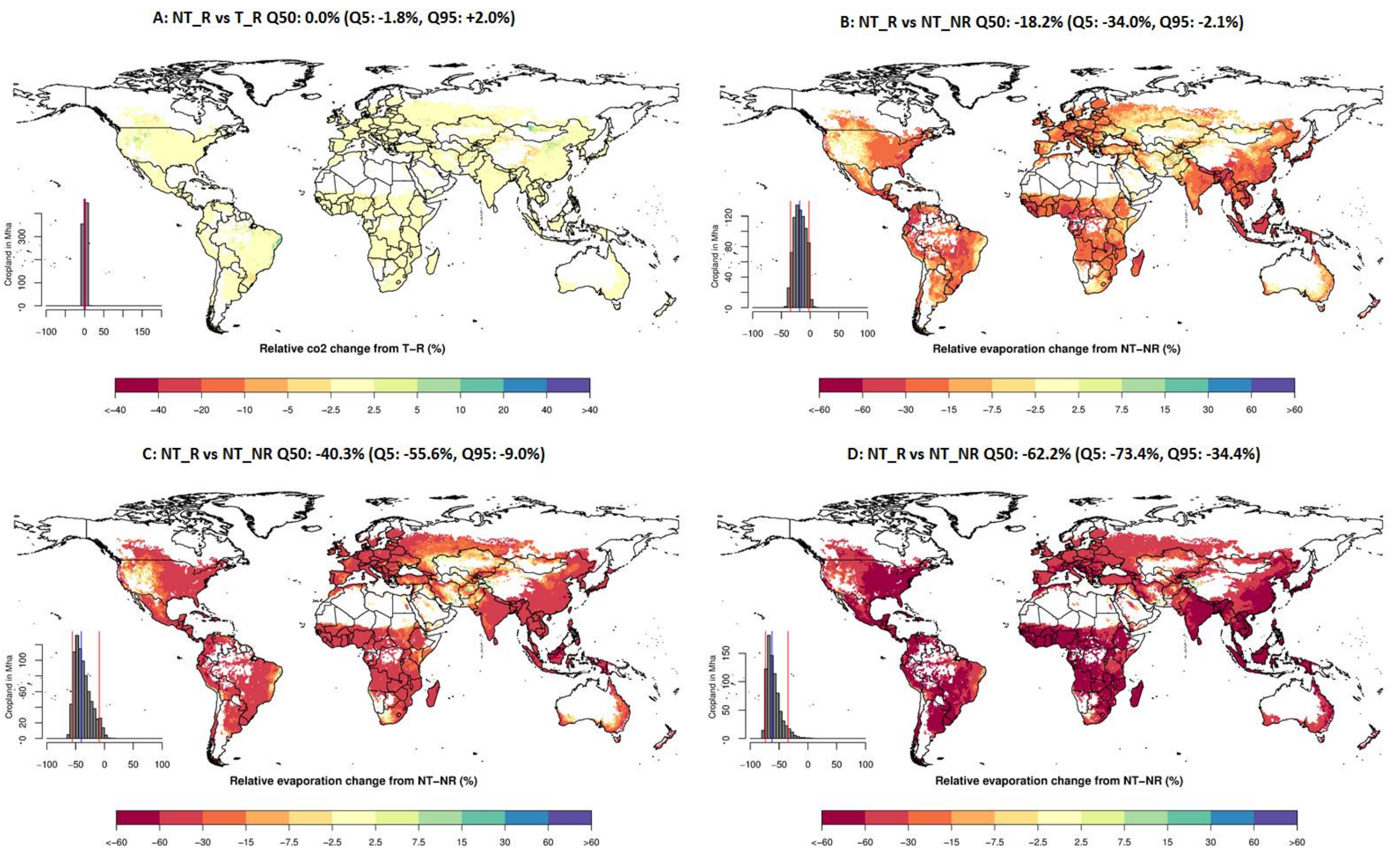
Appendix – Fig. 4: Relative topsoil and litter carbon change for T_NR vs. NT_NR after ten years of experiment duration (A), Relative CO_2 change for T_NR vs. NT_NR after ten years of experiment duration (B).



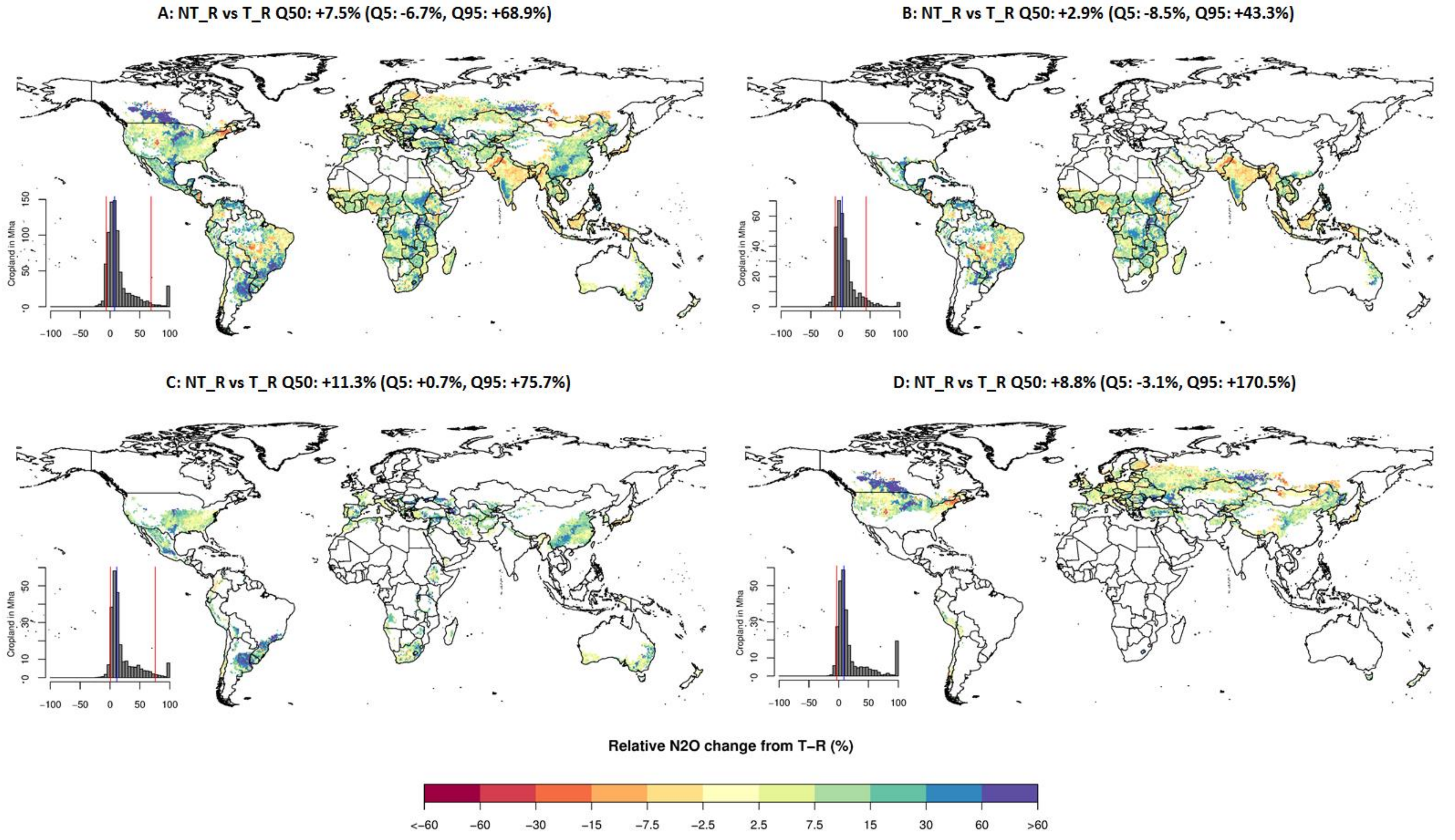
Appendix – Fig. 5(A): Overview of residue pools with corresponding decomposition variables.



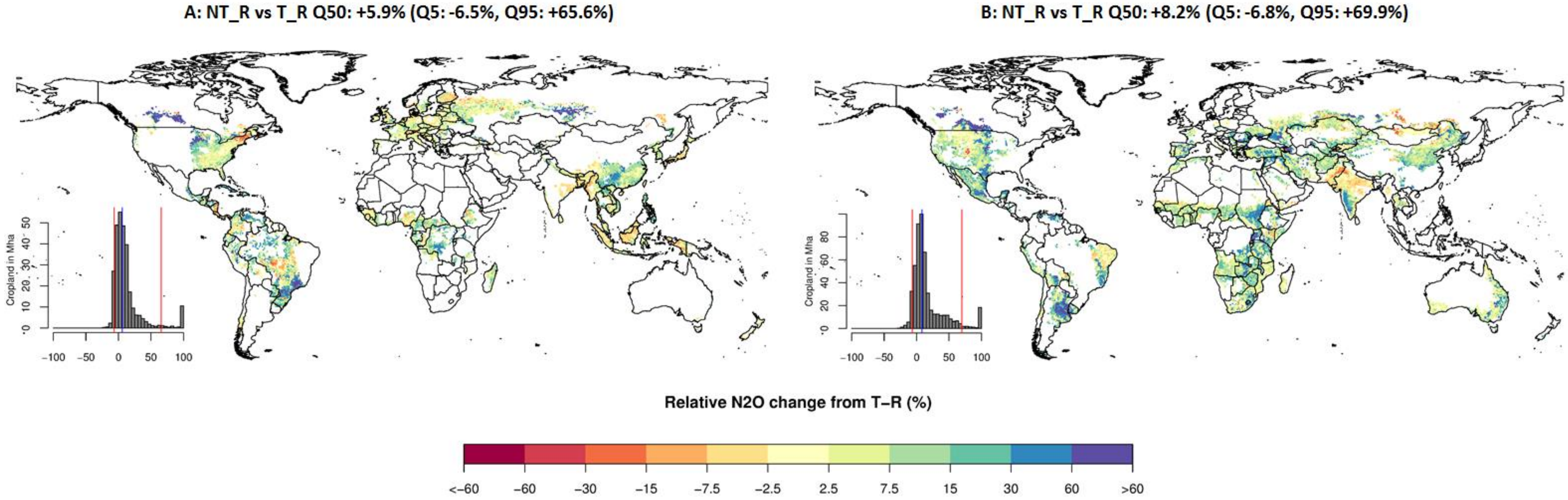
Appendix – Fig. 5(B): Overview of residue pools and the new pool for incorporated residues with corresponding decomposition variables.



Appendix – Fig. 6: Relative CO_2 emission change for NT_R vs. T_R from bare soil experiment for the first three years with C m^{-2} yr^{-1} fixed residue amount input (A), relative soil evaporation change for NT_R vs. NT_NR from the bare soil experiment for the first three years with 75g C m^{-2} yr^{-1} fixed residue amount input (B), relative soil evaporation change for NT_R vs. NT_NR from bare soil experiment for the first three years with 150g C m^{-2} yr^{-1} fixed residue amount input (C), Relative soil evaporation change for NT_R vs. NT_NR from bare soil experiment for the first three years with 300g C m^{-2} yr^{-1} fixed residue amount input (D).



~~Appendix – Fig. 7: Relative changes in N_2O emissions compared to T_R (A), Relative changes in N_2O emissions compared to T_R in tropical regions (B), Relative changes in N_2O emissions compared to T_R in the warm temperate regions (C), Relative changes in N_2O emissions compared to T_R in the cold temperate regions (D).~~



Appendix – Fig. 8: Relative changes in N_2O emissions compared to T_R in the humid regions (A), Relative changes in N_2O emissions compared to T_R in the arid regions (B).

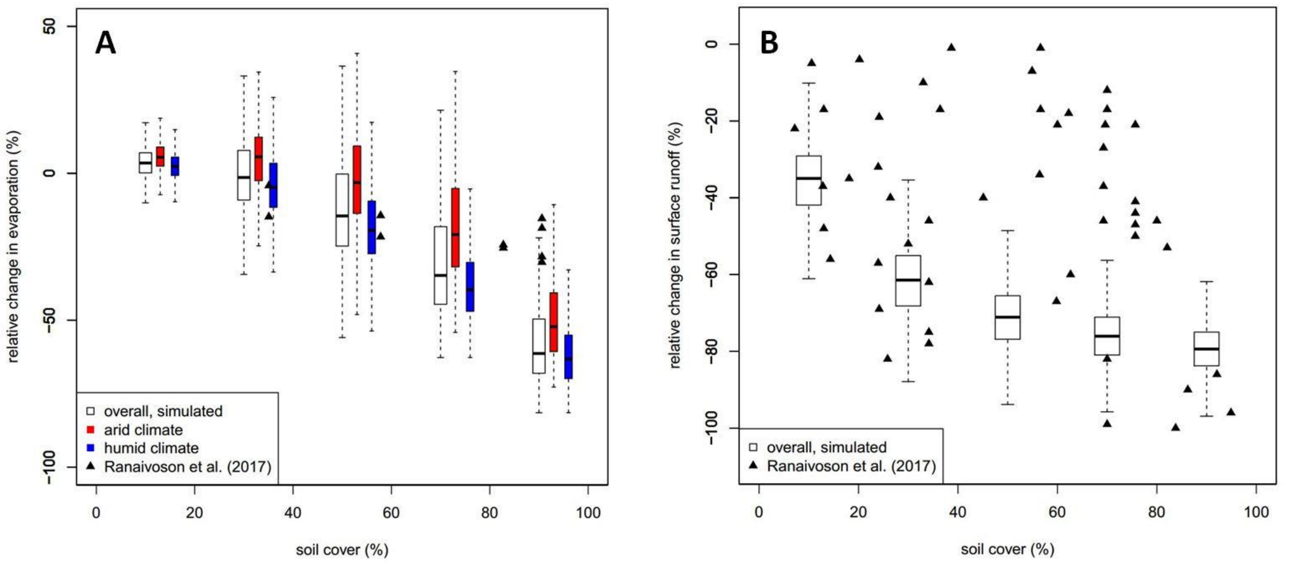


Figure 4: Relative change in evaporation (A) and surface runoff (B) relative to soil cover from surface residues for different soil cover values of 10, 30, 50, 70 and 90% (simulation NT_R_bs1 to NT_R_bs5 vs NT_NR_bs, respectively). For better visibility, the red and blue boxplots are plotted next to the overall boxplots, but correspond to the soil cover value of the overall simulation (empty boxes).

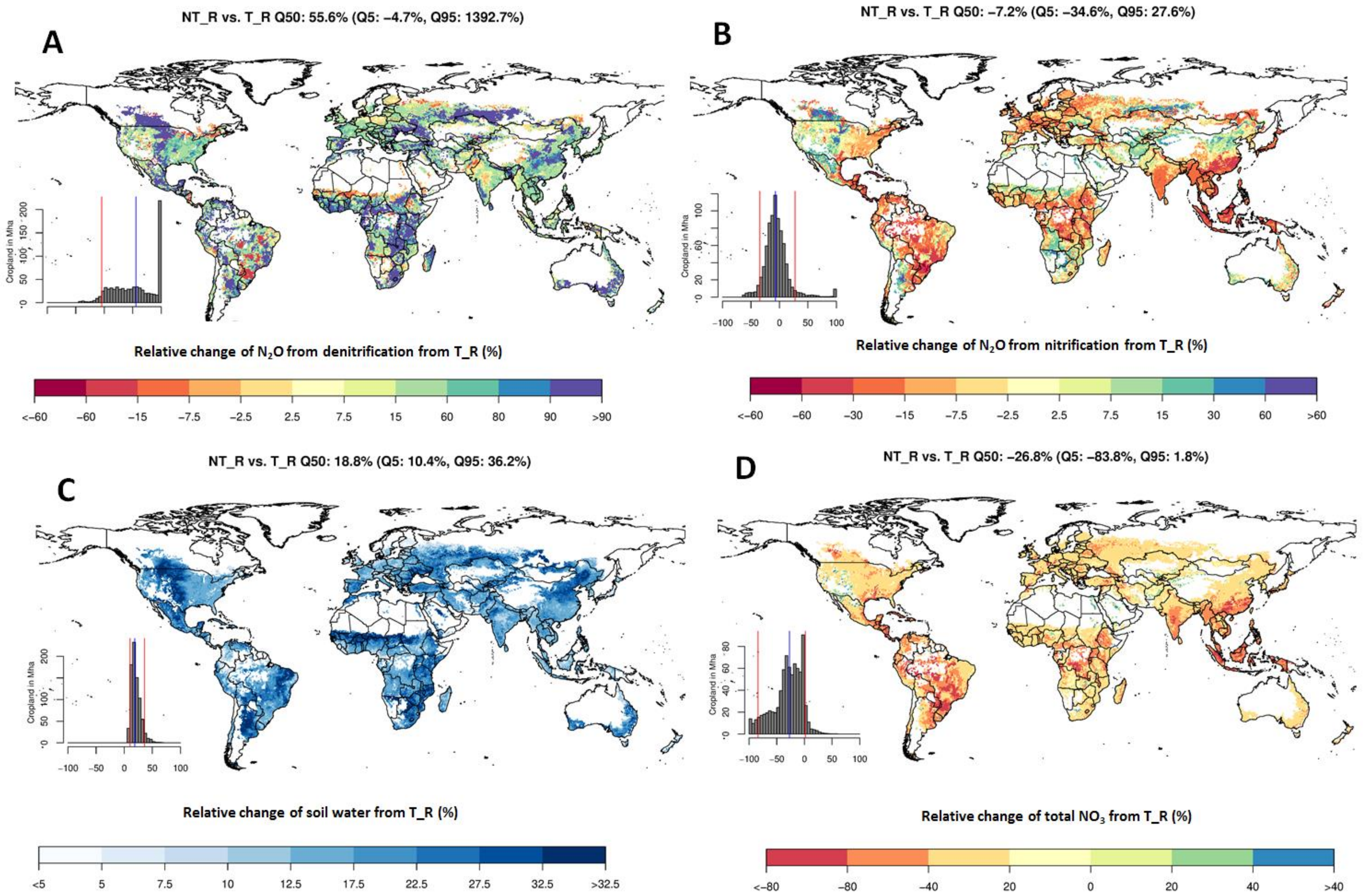
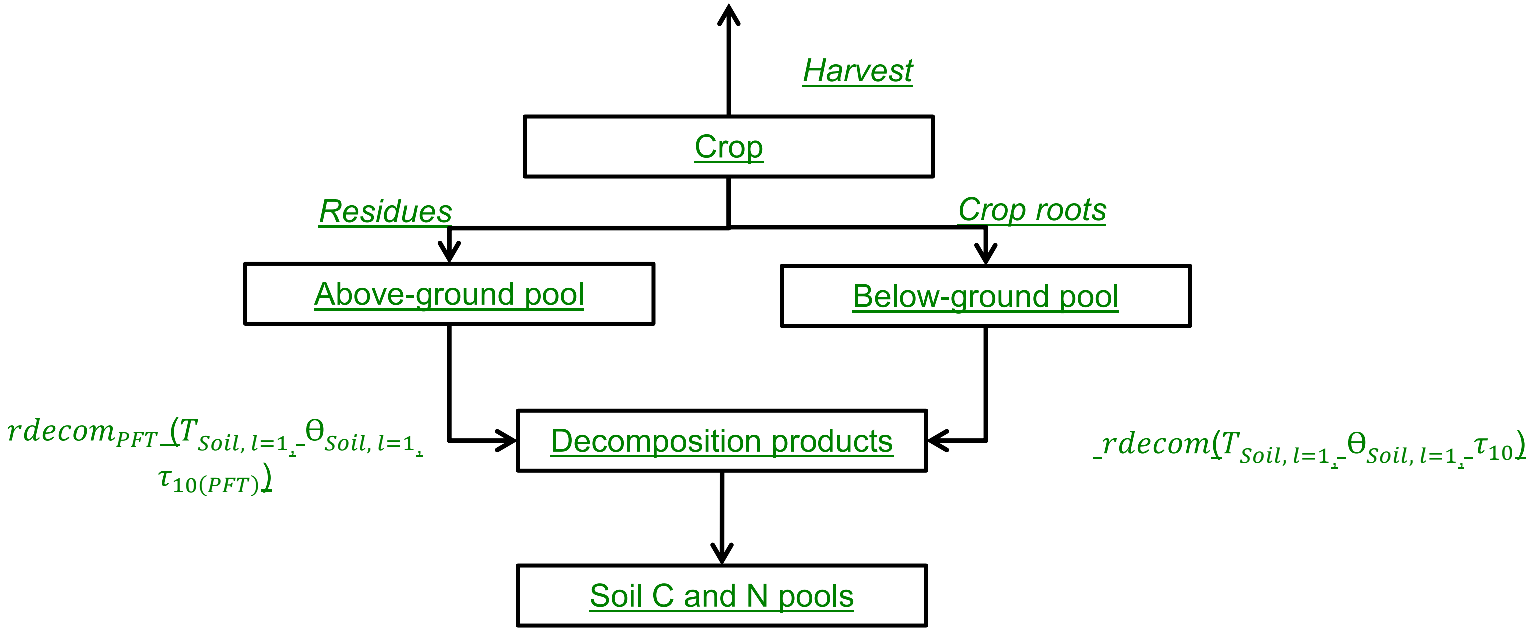
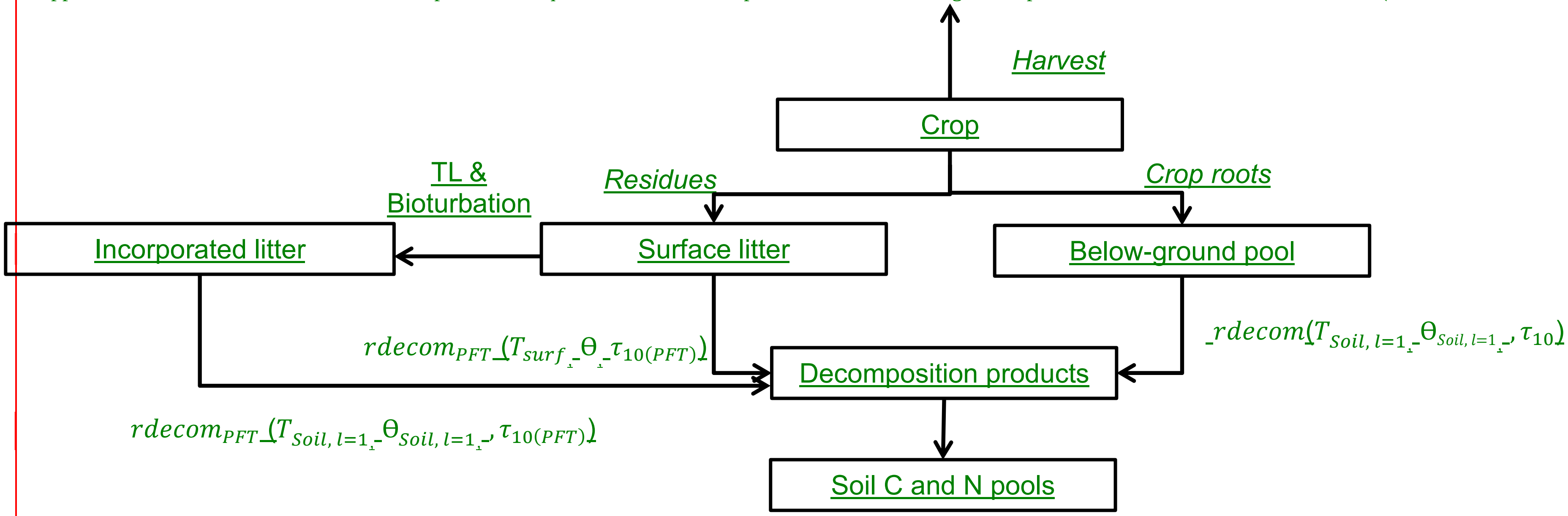


Figure 5: Relative changes for the average of the first three years of NT_R vs. T_R for denitrification (A), nitrification (B), soil water content (C) and NO_3^- (D).

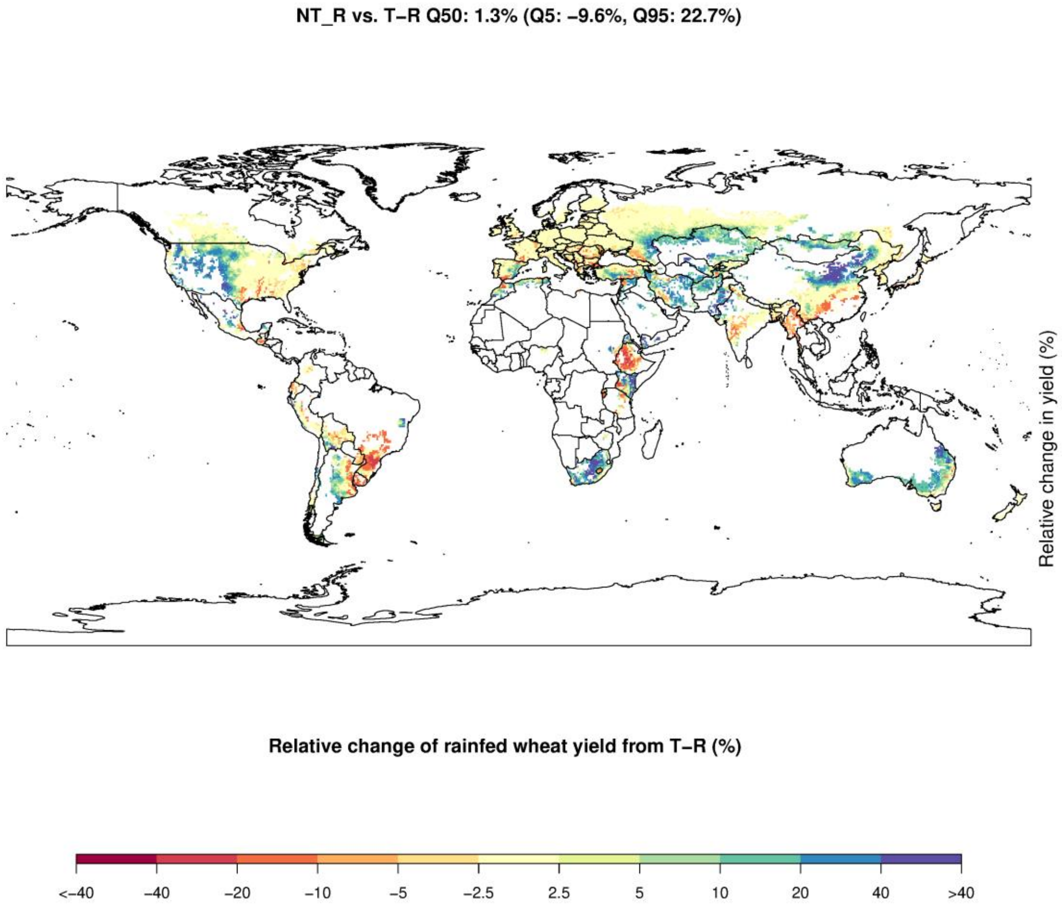


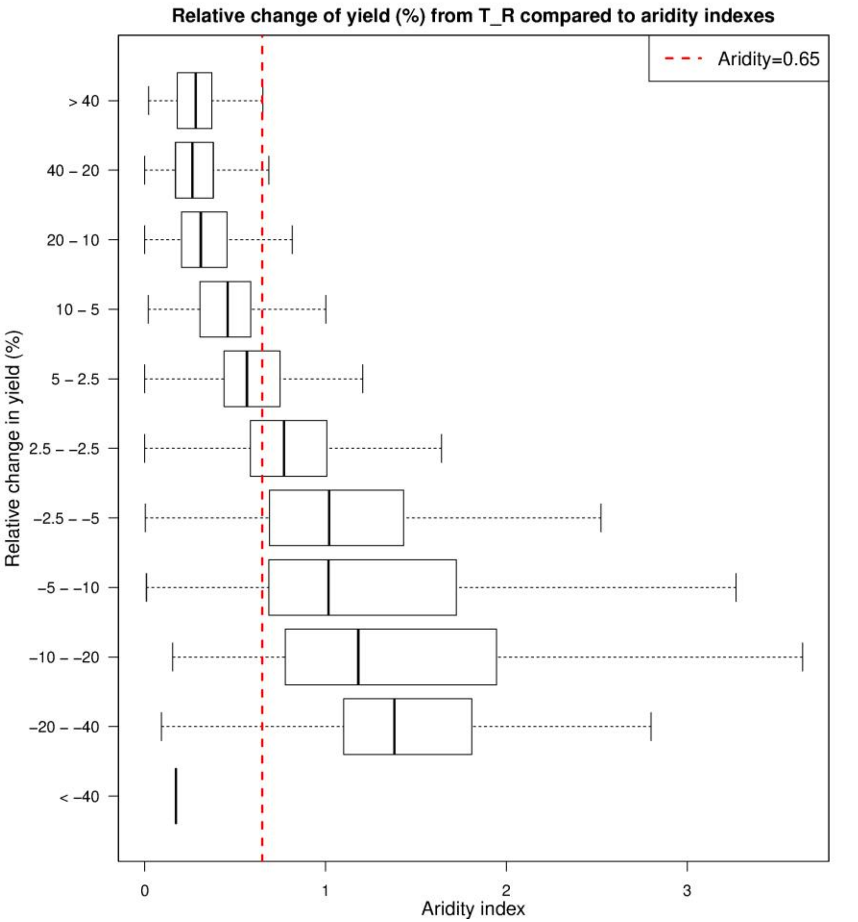
Appendix 1A: Overview of residue and soil pools with equations of the decomposition rates in the original implementation of the LPJmL5.0 version (von Bloh et al., 2018).



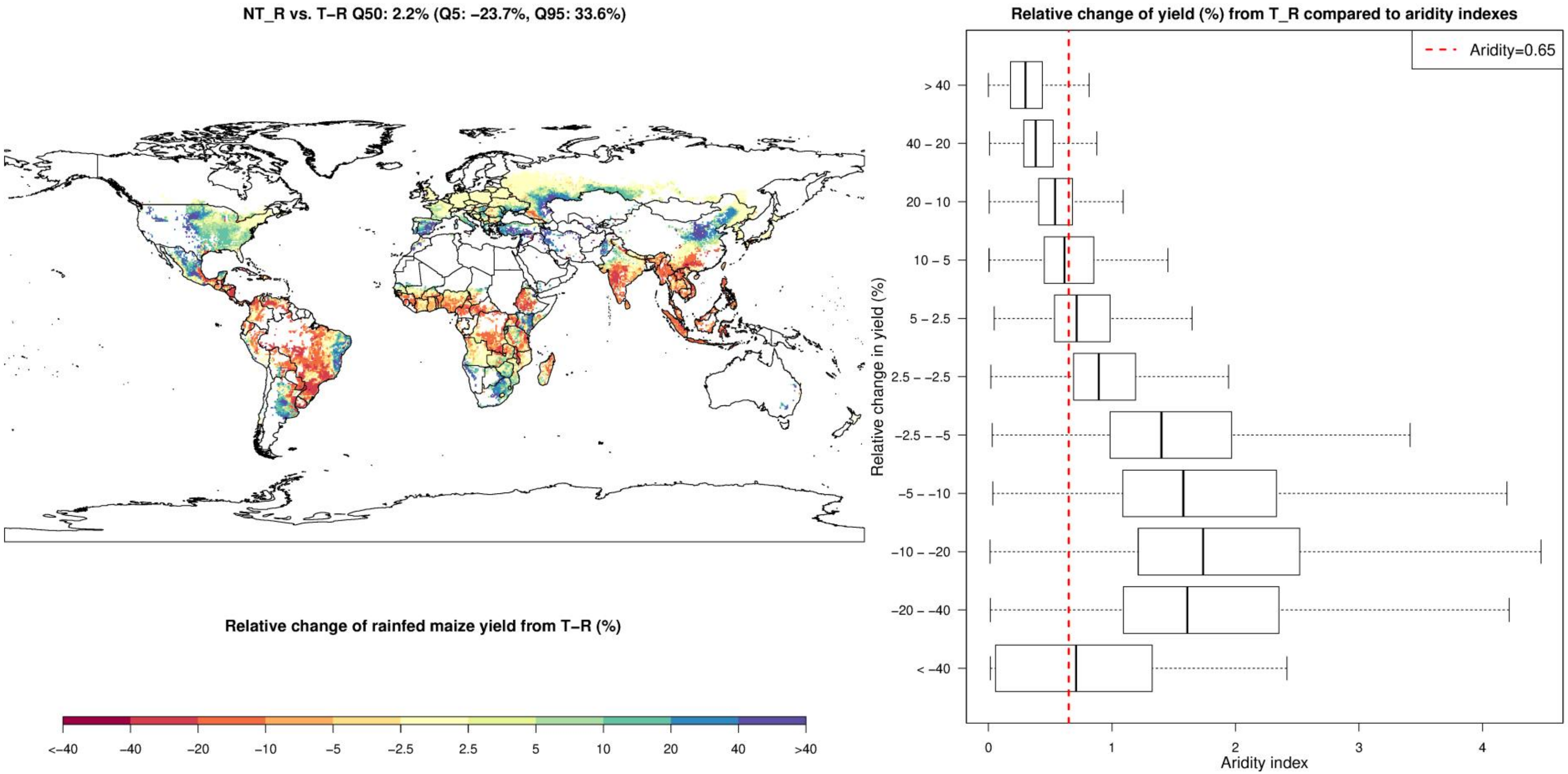
Appendix 1B: Overview of residue and soil pools with equations of the decomposition rates in this new model implementation (LPJmL5.0-tillage version).

A

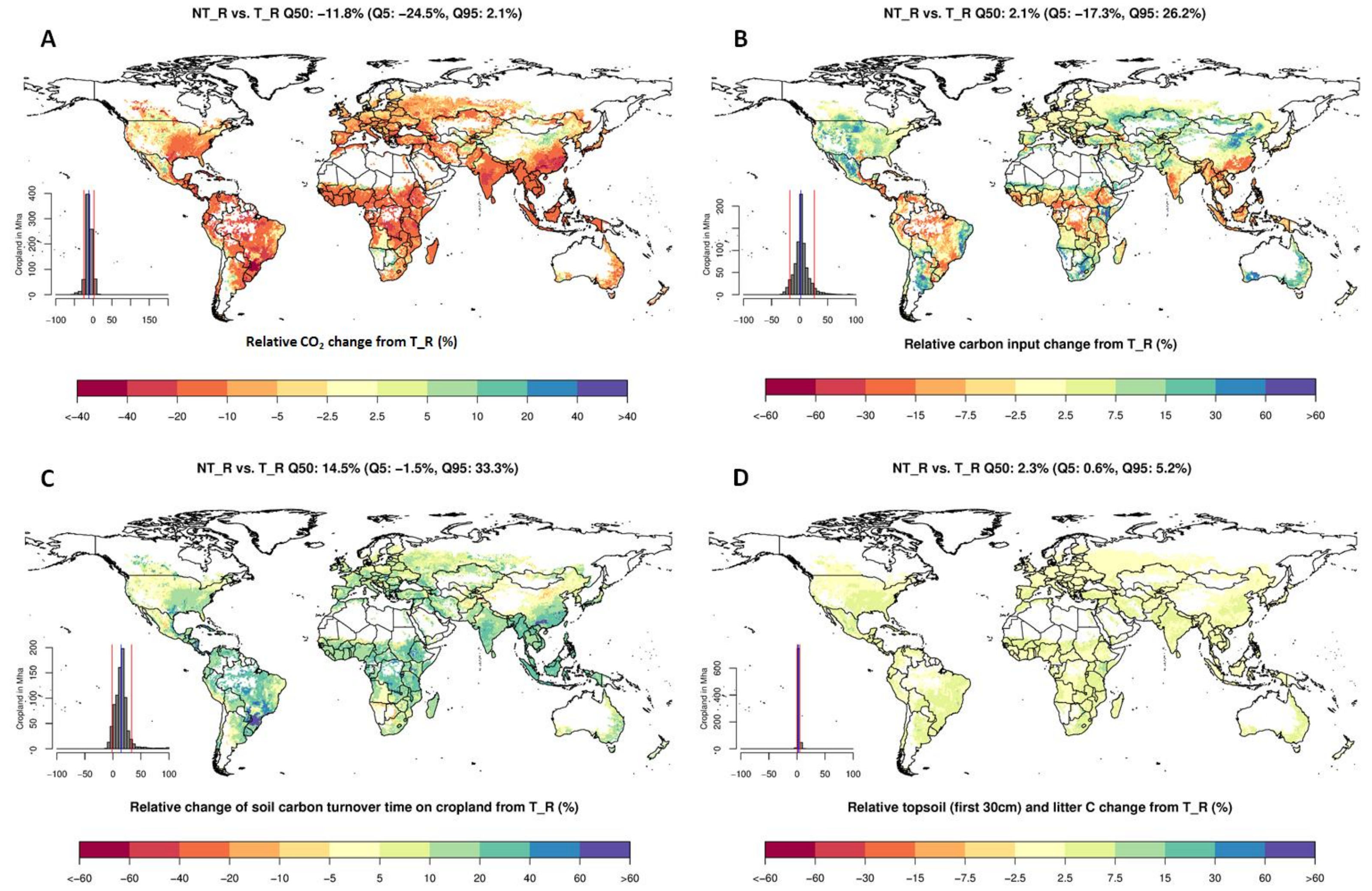

NT_R vs. T−R Q50: 1.3% (Q5: −9.6%, Q95: 22.7%)
Relative change of rainfed wheat yield from T−R (%)
<−40 −40 −20 −10 −5 −2.5 2.5 5 10 20 40 >40


Relative change of yield (%) from T_R compared to aridity indexes
Aridity=0.65
Relative change in yield (%)
> 40
40 − 20
20 − 10
10 − 5
5 − 2.5
2.5 − −2.5
−2.5 − −5
−5 − −10
−10 − −20
−20 − −40
< −40
0 1 2 3
Aridity index

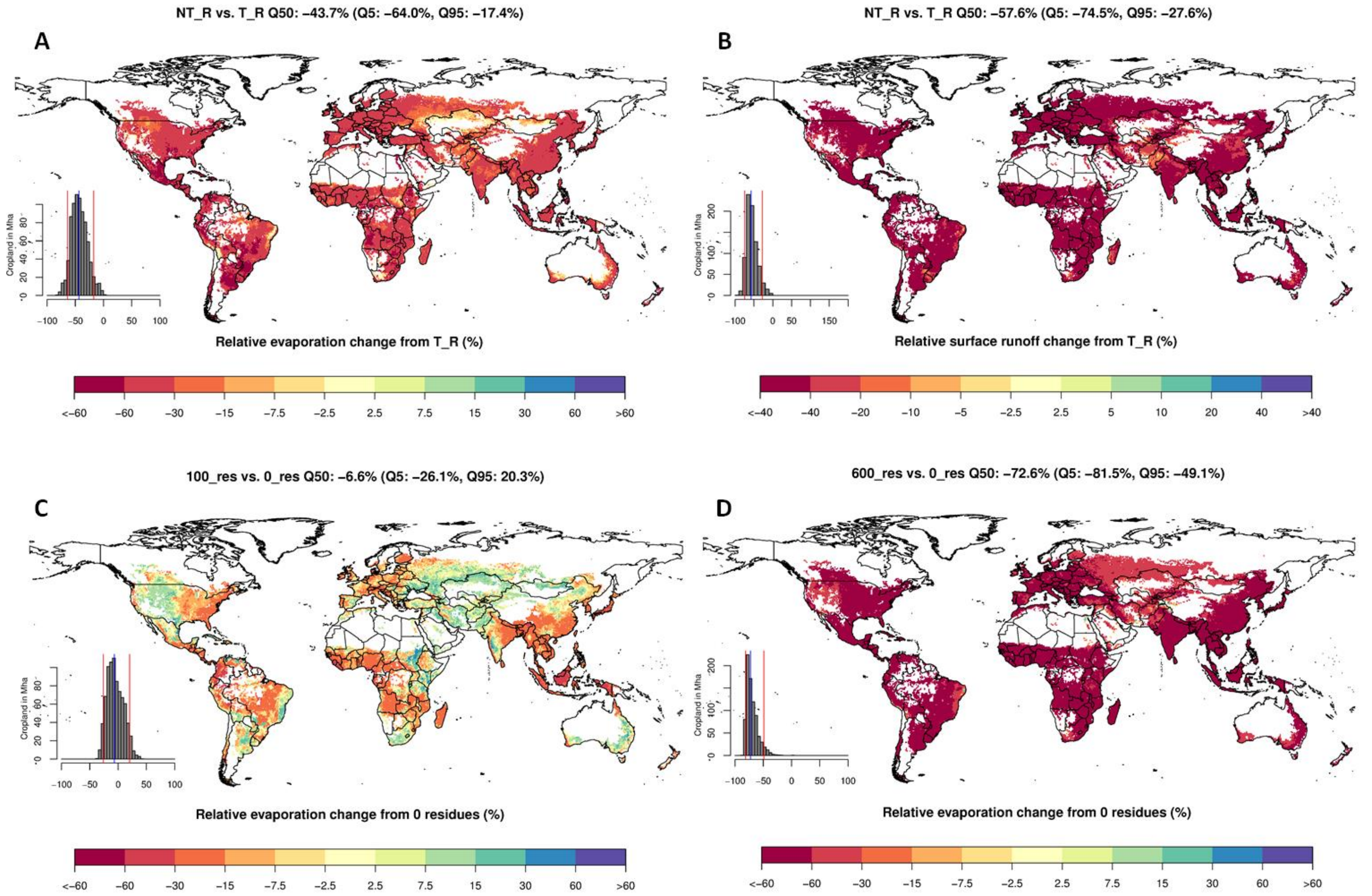
B



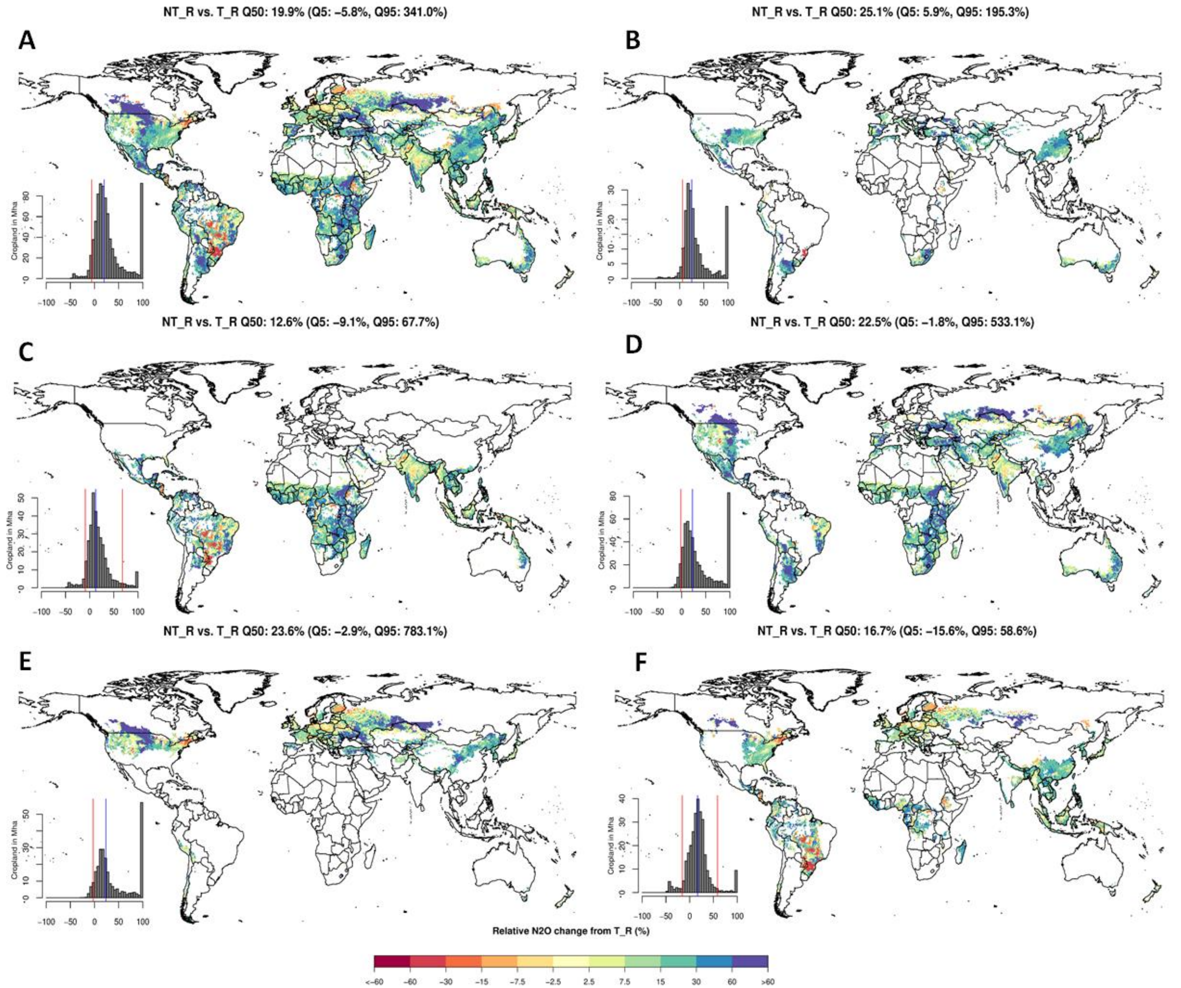
Appendix 2: Relative yield changes for rain-fed wheat (A) and rain-fed maize (B) compared to aridity indexes for the average of the first three years of NT_R vs. T_R.



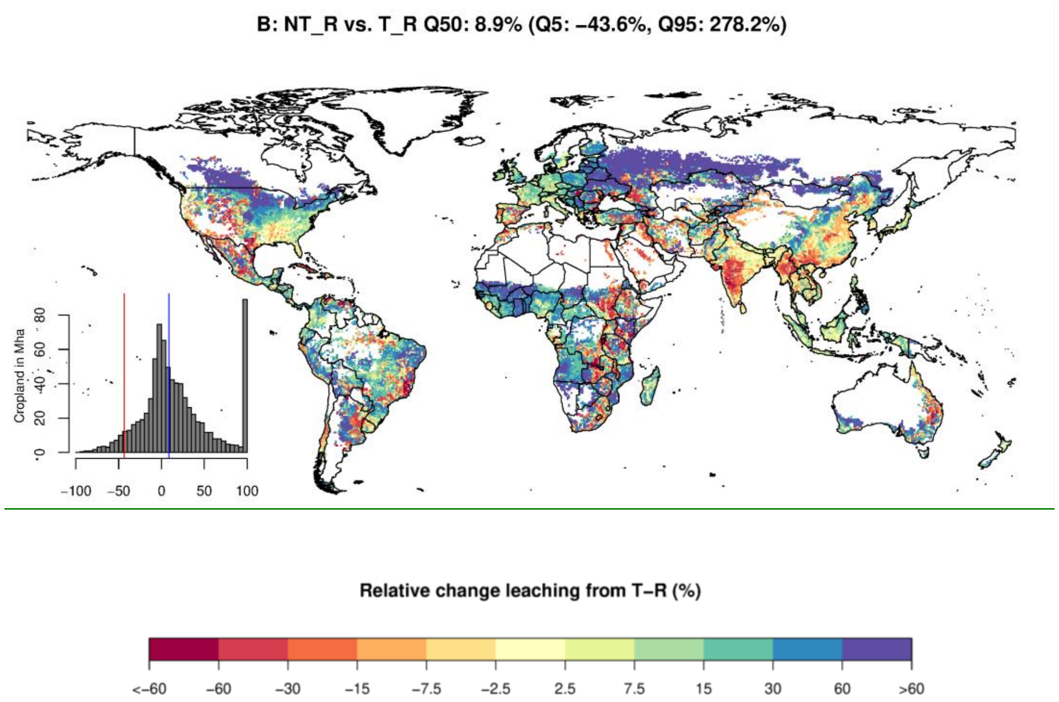
Appendix 3: Relative C dynamics for NT_R vs. T_R comparison after 10 years (average of year 9-11) of the simulation experiment for relative CO_2 change (A), relative C input change (B), relative change of soil C turnover time (C) and relative topsoil and litter C change (D).



Appendix 4: Relative changes in evaporation (A) and surface runoff (B) for NT_R vs. T_R for the average of the first 3 years of the simulation experiment and for bare soil experiments with fixed dry matter loads of 100 g m^2 (C) and 600 g m^2 (D) compared to bare soil with no residues.



Appendix 5: Relative changes for N_2O dynamics for the average of the first three years of NT_R vs. T_R of the simulation experiment for different climates – overall (A), warm-temperate (B), tropical (C), arid (D), cold-temperate (E) and humid (F).



Appendix 6: Relative changes for leaching (NO_3^-) dynamics for the average of the first three years for NT_R vs. T_R simulation experiment.