

Interactive comment on “Representing anthropogenic gross land use change, wood harvest and forest age dynamics in a global vegetation model ORCHIDEE-MICT (r4259)” by Chao Yue et al.

Anonymous Referee #1

Received and published: 1 August 2017

General Comment:

This study touches on the issue of the representation of shifting cultivation in the dynamic vegetation model. The new model features including a better description on PFTs (plant function types) demography, wood harvest and shifting cultivation at a sub-grid scale. The behavior of the enhanced model was tested both at a small scale and at a regional scale over an old growth forest (Miombo/dry woodlands) in South Africa. The model result shows that the new development has a robust representation of shifting cultivation during a long-term simulation period and the carbon emission due to the land use change has been underestimated without the consideration of gross land use change (including shifting cultivation, age class PFT and wood harvest). The most important term for this net emission is contributed from the biomass burning due to shifting cultivation activities (the F_{Inst} term in Eq. (3)). The manuscript was written in a good shape with a detail model description and its experimental design, and the new model feature opens the opportunities for the scientific community to study the research issue such as the effects of shifting cultivation between different biomes on the climate from different soil types and climate zones.

[We appreciate the reviewer's efforts to review our paper. Please see our point-to-point response as below. Major revised texts in response to the reviewer's request are tracked in the updated manuscript.](#)

Specific Comment:

I suggest the authors to provide a more detailed description and adequate reference of each term in the Eq. (3), which are the crucial parts of mathematical representation for the biophysical/chemical processes. For example, the “ F_{HR} ” term is often parameterised as function of surface temperature, and it also could be parameterised as function both of surface temperature and soil moisture (Chang et al. 2008). In the view of result presented by the authors, “ F_{Inst} ” term is the major source of the net CO₂ emission from the shifting cultivation between forests and croplands. I would also like to understand the sensitivity of this term to the state variables, such as soil temperature, soil carbon stock and ect. in the model.

Reference: Chang, S.-C., K.-H. Tseng, Y.-J. Hsia, C.-P. Wang, and J.-T. Wu. 2008. Soil respiration in a subtropical montane cloud forest in Taiwan. *Agric. Forest Meteorol.* 148: 788-798

All the terms in Eq. (3) are now explained in more details. Further references are provided when necessary. F_{Inst} represents the instant carbon fluxes to the atmosphere in forest clearing and is determined in the model on an annual time scale. It depends only on the wood mass of the forests being cleared and not directly on soil status including the temperature and moisture. This is now explained clearly in the revised texts.

We added the following texts in Sect. 2.1.5: “Carbon in the two wood product pools is then released into the atmosphere according to their respective turnover time, and this flux contributes to the overall land carbon balance as a source term (see the next section).”, “Agricultural harvest and associated fluxes to the atmosphere through food consumption or livestock feeding are assumed to happen locally in the model, without considering spatial relocation through international trade.”. We added the following texts in Sect. 2.2.1: “ F_{Inst} and F_{Wood} are both fluxes on an annual time scale that depend only on wood mass at the time of forest clearing and the respective wood product degradation rates (see Sect. 2.1.5). FHR is simulated at a time step of 30 minutes and depend on soil temperature and moisture. F_{Fire} is simulated with a prognostic fire module SPITFIRE (Yue et al., 2015).”

In this paragraph (P8L241-L245), I was confused about the description of the recruitment in a forest. Does the natural recruitment in a forest increase the original forest cover fraction (Diluted the carbon stock)? Or, the forest cover fraction is always fixed and the recruitment only increases the carbon stock.

We apologize for this confusion in the original text. The focus here is to describe how forest cover fractions are handled in the process of natural mortality and recruitment, as our paper focuses on land cover change representation in the model. Natural recruitment from regeneration in a forest does not increase the original forest cover fraction. It does not either dilute the existing carbon stock (here, the original texts are inaccurate in its description). Instead, recruitment increases individual density and renews part of leaves (by updating leaf age composition in the model). The recruited sapling biomass is incorporated into the existing biomass only when the latter is virtually zero while a larger-than-zero ground fraction is prescribed. We revised the relevant texts in the paper as below and hope it is clearer (Sect. 2.1.3):

Natural forest mortality in ORCHIDEE could be either prescribed as a constant rate or dynamically simulated, but mortality takes effects by reducing the amount of existing biomass only, with the coverage of the concerned forest patch being unchanged. Likewise, recruitment increases forest individual density and update leaf age composition and other relevant variables, but again, forest coverage remains unchanged. These features are necessary, as the original ORCHIDEE model does not take into account forest demography. As explained in Krinner et al. (2015, page 8), recruitment sapling biomass is only incorporated when the existing biomasses is virtually zero while a larger-than-zero ground coverage is prescribed. These features remain the same in the case of with sub-grid cohorts, i.e., forest mortality or natural recruitment does not modify forest cohort ground coverage. In addition, forest mortality and subsequent regeneration due to forest fires are handled in a similar manner.

The author choose a dry woodland as an example to demonstrate the model behavior of shifting cultivation at a dry and warm climate zone. Regarding to the design of the land surface model (ORCHIDEE) is for a large scale study, I think it would be able to apply this new feature for a

tropical peat land forest and the model behavior should be also welcome and interesting for the readers in the Earth System Modeling community.

We agree with the reviewer that forest clearing in tropical peat land forest can be an interesting case to apply our model. In a companion paper (<https://www.biogeosciences-discuss.net/bg-2017-329/>) where we apply our model to investigate historical land-use change carbon emissions from shifting cultivation, there are some shifting cultivation activities in tropical Asia being included. However, the hydrological impacts on carbon due to land use change on peat-land forest must have not been adequately represented mainly because peat-land-related hydrological process and soil processes are not represented in the model version used here. There is a parallel model development in ORCHIDEE aiming for including peat land process (<https://www.geosci-model-dev-discuss.net/gmd-2017-155/>). In the future, these developments could be integrated for a more sensible representation of peat land-related land use change.

Technical Comment:

P2L59: the definition of “M” 10^6 (million) or 10^9 (mega)?

It means 10^6 (million). This is indicated in the revised manuscript.

P2L65: reference of “Hansis et al. 2015” is missing the reference list

Done.

P4L110: Some recent developments. . . , please cite more references

In response to the comments by other reviewers as well, we have added an overview table of DGVMs (Tabel 1 in the revised text) having implemented gross land use change, and more references are added in the introduction section. Please refer to the revised introduction section.

P5L158: ...”Fig 1d” ... to ...”Fig. 1d”...

Done.

P8L239: . . .are properly defined. Please explain how to define the criteria for the cohort thresholds.

This has been explained in detail in Sect. 2.2.3 in the original manuscript. To not increase the manuscript length by making repeats, the section 2.2.3 is now cited in the Sect. 2.1.3.

P9L279: the index i, j have been already used. It should be replaced by another indices, such as k, l .

We argue that it is convenient and an implicitly agreed practice to denote an element of a matrix M as M_{ij} . In our case we suppose readers can easily distinguish that here the indices i, j are different from the ones used before in Sect. 2.1.3. So this notation is maintained.

P13L395, L404: The description of F_{Fire} for Eq. (3) is missed.

It is explained in the revised texts, in response as well to the first specific comment by the reviewer.

P13L414: ...”simulations and Le Quere et al. (2016)”... I suggest to rephrase it to . . .”simulations and the existing global carbon budget dataset (Le Quere et al., 2016)”.

Done.

P15L473-L474: six CFTs but only five ages (3, 9, 15, 30, 50) in the text

The last cohort (Cohort₆) corresponds to the mature or primary forest and therefore its age (i.e., years) is not given as an exact number. To remove the potential confusion, we denote the age of Cohort₆ as >50 years in the revised manuscript. We revised the sentence to “*The woody mass thresholds are set in a way that they correspond roughly to the woody masses at ages of 3, 9, 15, 30, 50 years, and the mature or primary forest (with an age greater than 50 years) during the spin-up simulation, respectively, for Cohort₁ to Cohort₆.*”

P15L481: the reason for choosing 65%.

This value here is chosen tentatively and more for a demonstration purpose. The key point is to separate agricultural lands (croplands and pastures) into two broad age groups assuming that they have different soil carbon stocks. In general, because changes of soil carbon stock following land use change are spatially highly diverse and depend on many factors including the land cover types before and after the transition, the model feature described here is more for informative demonstrating purpose rather than having solid scientific significance. This is primarily due to the fact that soil moisture is simulated in the model on the basis of water columns, and soil temperature over the whole grid cell rather than cohorts, as explained in the text (Sect. 2.2.3, 2nd paragraph). To fully track the soil carbon trajectory after land use change, a much larger number of cohorts for herbaceous vegetation are needed, but this is limited by the computing power when running simulation over the globe. Overall, this feature is more like a “place holder” whose function needs to be explored and parameterization has to be improved in the future model application. We inserted at the end of Sect. 2.2.3 the following sentences to clarify this: “*Overall, this feature of separating herbaceous MTCs into multiple cohorts is coded more as a “place holder” for the current stage of model development rather than having solid scientific significance. To fully track soil carbon stocks of different vegetation types and their transient changes following land use change, a much larger number of cohorts are needed.*”

P19L599: The Fig. 9 sub-index for “b” can’t find the Figure 9. Please revise it for the consistence between the context and figure.

Fig. 9 is now revised.

P21L667-L669: Please give an example for the possible missing process in the land use change.

The example is given in the original text, e.g., gross land use change.

P22L702: The citation of “Hurtt et al. 2016” is not in the reference list.

This should have been Hurtt et al. 2006 but now it is replaced with Hurtt et al. 2011 exclusively.

P22L711: Typo: . . .O”R”CHIDEE-MICT. . .

Thanks for pointing this out. We apologize for this typo. It has been corrected.

P22L723: . . .”is need to streamline land use”. . . This is a bad English structure. I would recommend to rephrase it as . . .”is needed to streamlining to land use”. . .

We change this sentence to: *But in general and over a long term, land use or land management decisions need to be integrated directly into DGVMs.*

P23L734-L736: It is a sentence with a bad English structure. Please rephrase it.

We modified these two sentences to make them more concrete: *These developments also make it possible to verify modeled global and regional forest age distribution using independent age information from either forest inventory or remote sensing. The model version used here has incorporated the developments in pasture and cropland modules (Chang et al., 2015; Wang et al., 2017). On a regional scale such as Europe, where the comprehensive forcing data are available, it is possible to go beyond the carbon emissions only by LUC activities, but also to include LUC-induced changes in emissions of other greenhouse gases such as methane and nitrogen oxide.*

P33L989: Add a line for “S_{age}” simulation. I was confused about the zero cover fraction for both Cohort4 and Cohort5. For a 100 year simulation, the Cohort4 and Cohort5 supposed to have dynamic changes in the cover fraction. Please explain the zero cover fraction for Cohort4 and Cohort5 in the main text.

The S_{age} simulation is shown as each individual cohort from Cohort₁ to Cohort₆. This is now explained more clearly in the revised figure caption. As this figure shows a simulation of an annual forest-cropland turnover of 5% of grid cell area and the clearing of forest targets primarily on Cohort₃, this cohort has been converted to cropland before having the chance to move to Cohort₄. This explains the zero fractions of Cohort₄ and Cohort₅. This point is also explained in the revised text as the following: *“As Cohort₃ is being constantly converted to cropland, it has never developed into Cohort₄ or Cohort₅. This explains the zero fractions of these two latter cohorts in Fig. 6f & 6g.”*

P36L1014: Please check the label of the Fig.9. sub-label “b” is missed.

This has been corrected.

Interactive comment on “Representing anthropogenic gross land use change, wood harvest and forest age dynamics in a global vegetation model ORCHIDEE-MICT (r4259)” by Chao Yue et al.

B. Stocker (Referee)

b.stocker@creaf.uab.cat Received and published: 18 September 2017

The paper by Yue et al. describes the implementation of gross land use change within the ORCHIDEE Dynamic Global Vegetation Model. This implementation relies on an explicit and separate treatment of six different age cohorts of land “patches”. C dynamics are simulated separately within each patch and cohort age priority for conversion from forest to agricultural land is specified explicitly. It is shown both at the level of an individual gridcell and at the regional scale (Southern Africa) that this leads to lower LUC-related CO₂ emissions compared to a simulation where age cohorts are not distinguished in a simulation that accounts for gross land use change.

This is a substantial and very complex step in model development and improves the realism of simulations of the anthropogenic land use change. The paper provides a detailed and in some parts rather technical and model-specific description of the implementation. It convincingly shows for a single example gridcell how biomass is simulated to accumulate and transition through cohorts of different age and how it reaches a dynamic steady state under constant gross land use change regime (no expansion, constant land turnover). In that sense, one can conclude that the model works - arguably the most important statement of this paper.

[R1] We appreciate the reviewer’s efforts to review our paper and thanks for the general positive comments. The most model-specific section is probably Sect. 2.1.3, where cohort implementation has been described in detail in ORCHIDEE-MICT. This is necessary for understanding other sections. Furthermore, this could also give insights to other similar DGVMs (e.g., JSBACH, CLM) to implement similar schemes. Sec. 2.1.4, as we can argue, might seem model-specific at the first sight but actually is not — because two key model features, i.e., the necessity to introduce a priority decision rule and allocation of LUC-impacted cohort on different underlying vegetation types, can be needed as well when other DGVMs will try to implement LUC processes with vegetation demography. Thus the development presented here can be potentially useful for other similar DGVMs. We take the chance of addressing the reviewer’s comments in the paragraph below to cite relevant studies and make close comparisons when describing our model development, to make the model descriptions more relevant for other DGVMs.

The authors then go on to investigate the effect of gross versus net land use change and the effect of separating six age cohorts (versus averaging all into a single age cohort) for land use change CO₂ emissions of southern Africa. They conclude that “emissions from bi-directional land turnover alone are 35% lower in Sage than Sageless. (abstract)” and that the effect of gross versus net is to increase emissions by a factor of 2 (for “S_ageless”) and 1.5 (for “S_age”). I have some

concerns regarding the presentation of these conclusions, and regarding the scope (investigating age cohort effects) itself. One more (major) issue is regarding model spin up (see further below).

As stated by the authors (1.87-90), the present paper is not the first one to implement a model for simulating gross land use transitions. Stocker et al. (2014) and Wilkenskjeld et al. (2014) are cited. However, the authors forgot to refer to Shevliakova et al. (2009), GBC, who also implemented multiple age cohorts for simulating gross land use change. It should also be made clear that at least Shevliakova et al. (2009) and Stocker et al. (2014) (not Wilkenskjeld, as far as I am aware) did make a distinction between at least two age cohorts. Referring to “traditional approaches where a single patch is used for a given land cover type” (abstract, 1.26) and presenting results of the simulation “S_ageless” as representative for “traditional approaches” is thus a bit misleading.

[R2] Thanks for the reviewer pointing out the work of Shevliakova et al. (2009) and Stocker et al. (2014). Such expression of “traditional approaches” is now removed in the texts. The model implementations of Shevliakova et al. (2009) and Stocker et al. (2014) are now discussed closely with our implementations in the revised text where relevant. Please refer to the revised introduction and discussion sections.

The present paper was submitted on 14 May 2017. On 26 July 2017, Yue, Ciais and Li submitted a paper to Biogeosciences Discussions (<https://www.biogeosciences-discuss.net/bg-2017-329/>), where the same model is applied to investigate essentially the same questions, but this time at the global scale. The regional focus of the present paper on southern Africa may appear arbitrary at first, but makes sense. Apparently, authors preferred to devote a full paper to model description and evaluation and a second full paper to a global application. In my view, this is a viable way to go and the large work that went into developing this model warrants two separate papers. However, I find the delineation of their respective scope a bit unsatisfying. Readers will likely be left asking themselves why authors didn't present results from global simulations in the present (GMDD) paper - a relatively small additional step in terms of additional work. Simultaneously, readers of the BGD paper might be left wondering what the additional insight of that paper is after already the GMDD paper concluded that accounting for separate age cohorts reduces the effect of gross versus net LUC emissions.

[R3] We greatly appreciate the reviewer's efforts to review both our papers and the holistic approach to the reviewing process. The separation of the two papers, and the arrangement of the contents for each of them, are based on several considerations: (1) It will be very lengthy to include both model developments and application in a single paper, so we decide to separate the work into two papers, with one focusing on model development description and exemplifying its application, and the other one focusing on the global application and implications for quantifying historical LUC emissions. We appreciate that the reviewer agreed on this approach. (2) The inclusion of forest demography and related cohorts is a key feature of the current paper. On top of this we implemented in the model a series of priority rules on which forest cohort to be targeted based on different LUC processes (Fig. 5). To exemplify the setting of forest cohort boundaries, and the impact of the implemented priority rule on forest demography dynamics (Fig. 9 in the original manuscript), a concrete example beyond the idealized single grid cell simulation is needed. This is the major motivation to include the southern Africa case study. (3) We argue that whether the results from the Southern Africa simulation belong to “illustrating the model

behaviour” or to “scientific results” can be discussed. We tend to include Fig. 9 to show the model behaviour as it is closely linked to the priority decision rules in LUC as explained in detail in 2.1.4. While in the bg-2017-329 paper, focus is given to the resulting LUC carbon emissions, their spatial and regional patterns and relevant comparisons with other studies. So the results in bg-2017-329 are not just a small step as argued by the reviewer, although the central message of that paper is in line with what’s found by the idealized site-scale simulation in the current paper. These arguments/motivations are now included briefly in the revised texts in the introduction section.

A solution for that is to reinforce the value of the present (GMDD) paper in terms of its model documentation and dissemination aspects. Section 2.1.4. is very technical and might be too specific for the ORCHIDEE model, limiting its value for a wider readership. Code is not made publicly accessible (only upon request) and the study is therefore not reproducible. However, authors note the “clearly defined border of the LUC module”. In my view, it would be highly beneficial for the present paper to provide open access, reproducible code along with the paper. The module itself should be able to be decoupled from the rest of ORCHIDEE and some “synthetic” simulations should be possible, where land use transitions and cohorts dynamics are simulated by published parts of code. (I don’t understand why this is not strictly required anyway for GMDD.)

[R4] As we described in the response to the reviewers’ first comment, Sect. 2.1.4 is necessary to understand the model behaviour and we believe it can also provide insights for other DGVMs. The model codes are in principle open source but according to the policy of the lab, the access is limited to registered users. A username and password will be given upon contact on the corresponding author in order to access the code. On the other hand, the developed module is complex, so interested readers are encouraged to contact the corresponding author to get some navigation through the codes and facilitate their understanding. We are confident that after some adaptation, the codes can be migrated into other models. However, it is challenging to design the codes as fully independent, isolated and pluggable into other DGVMs readily, because to the least extent, the codes are intended to work in the ORCHIDEE code environment.

In any case, I encourage that the authors find a solution to finding a better delineation between their parallel submissions currently under review here and in BGD.

[R5] Based on our responses above (R3), and in view of the reviewer’s comments on our parallel bg-2017-329 paper, we revised both papers to make a clearer delineation in their scopes: (1) scopes are clearly defined in each introduction, with the current GMD paper focusing on model documentation and examination / illustration of model behaviour and the BG-paper focusing on model application at global scale with a focus on the 20th Century. (2) Fig. 10 in the original manuscript, along with relevant method sections have been removed in the revised GMD paper, with Fig. 9 being kept focusing on cohort dynamics resulting from historical land use change that are highly relevant to our implemented cohort priority rules in the model. (3) Model documentation is enhanced, with dissemination aspects being strengthened. We further add a Table 2 to summarize the implemented LUC decision rules. In particular, DGVMs having already implemented gross land use change have been referred to and discussed in parallel with our implementation where relevant in the revised manuscript, in response to several reviewers’ comments on this aspect. (4) We performed a series of additional simulations to investigate the

sensitivity of derived land turnover emissions to the targeted cohort age and biomass in the African continent, to investigate the impact of delineating different cohorts on the simulated land use emissions. But this result is included in the BG-paper as we think it's more relevant there. (5) In the BG-paper, the implication of our finding, i.e., lower emissions when taking into account age structure, is further discussed in relevance with our model implementation and the work of Arneeth et al. (2017).

Regarding model spin up: Fig. 6 shows that if a constant land turnover rate is applied during the transient simulation, but not during spinup, biomass C stocks attain the “wrong” equilibrium. I.e. stocks decline after being subjected to continuous land turnover to a new steady state, reached after around 50 years (under a tropical climate). Soil C stocks likely take longer to attain a new steady state and in cold climates even more so. If simulations are evaluated from the start of the transient simulation, then land-atmosphere C fluxes related to reaching this new steady state confound results. How is this treated when, for example, doing a historical simulation starting in 1850? Shouldn't a continuous land turnover pattern be applied already during spin up in order to avoid these disequilibrium fluxes?

[R6] We agree with the reviewer that ideally some form of land turnover should be included in the spin-up runs. Likewise, natural stand-replacing disturbances should be included as well. However, unfortunately, neither of them is included in our current simulation. This point is acknowledged in the revised BG-paper where LUC emissions are examined in more details. On the other hand, as we start our simulation from Year 1501 in BG paper, LUC emissions from 1850 are unlikely impacted by a lack of land turnover in the spin-up and the estimations can still hold. This latter point is also discussed in the revised BG-paper.

MINOR:

* 1.61: . . . emissions *of CO2* (Houghton et al., 1999) . . .

Done.

* 1. 67 “Given the importance of historical LUC emissions and its large uncertainty, a more realistic representation of LUC processes and land management in DGVMs is desirable”.
Improving realism rarely reduces uncertainty (~model spread).

We agree on this. We changed the original sentence to “*Given the importance of understanding historical LUC emissions in projecting the future land-based mitigation potential, a more realistic representation of LUC processes and land management in DGVMs is desirable.*”

* The net-versus-gross LUC question is introduced only on 1.73 - in my view too late. Preceding paragraphs detract attention from the questions at hand here.

We have shortened the 1st and 2nd paragraph. We believe the lengths of these two paragraphs after revision provide a minimum scientific background of land-use change emissions before diving into the more technical description of gross versus net land use change.

* As pointed out on 1.95, accounting for gross land use change is relevant more generally for

appropriately simulating sub-grid scale bi-directional land use transitions and is not only relevant in shifting cultivation agriculture. The term shifting cultivation refers to a specific form of smallholder agriculture and doesn't encompass all sub-grid scale bi-directional land use transitions. I am aware that the previous literature on modelling these effects used the terms shifting cultivation and gross land use change (or land turnover) more or less interchangeably. Maybe worth stating here (in introduction) what shifting cultivation actually is (see Heinimann et al., 2017, PLOSOne: <https://doi.org/10.1371/journal.pone.0184479>).

We inserted a brief definition of shifting cultivation in this paragraph following the suggestion by the reviewer. Heinimann et al. 2017 is cited as well. The inserted texts are: “*A typical example is shifting cultivation, a form of smallholder subsistence agriculture primarily occurring in tropical regions that involves clearing a forest for a non-permanent cropland, which is often abandoned later. Shifting cultivation was historically important in many tropical regions for the subsistence of indigenous people (Hurt et al., 2006; Lanly, 1985) although more recently it has been in the process of being superseded by more intensified land management (Heinimann et al., 2017).*”

* 1.105: reference for “dilution approach”?*

This term occurs in the ORCHIDEE documentation but cannot be found in literature. Thus it is removed from the revised texts.

1.122 “r3247”: Better use SVN tags than SVN version numbers for reference.

Following the reviewer's suggestion, the code has been tagged as ORCHIDEE-MICT v8.4.2. The title is also changed accordingly.

* 1.277 (Eq.1):

The reviewer may have some comments here but it seems they did not show up.

* Fig. 6: Very nice plot! Would be very informative to have a curve for total biomass across all cohorts in the simulation with age distinction (to make it comparable to the black curve for S_{ageless}).

Biomass carbon stocks for all cohorts with age distinction, and for the single forest patch in the S_{ageless} simulation are all based on per unit area of forest. The different cohorts in S_{age} simulation are spatially distinct or separated so it does not make sense to add them together.

* Fig. 7: Is this figure referenced in the text? Where?

Yes. Fig. 7a and 7b are discussed in section 3.1.2 in the text.

Interactive comment on “Representing anthropogenic gross land use change, wood harvest and forest age dynamics in a global vegetation model ORCHIDEE-MICT (r4259)” by Chao Yue et al.

J.E.M.S. Nabel

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The manuscript by Yue and colleagues presents model development in ORCHIDEE-MICT, incorporating a forest age structure and gross land use transitions, including shifting cultivation. Both aspects were subject to several papers in the recent years and it would be helpful if the authors set their implementation and their findings more (and more accurately) in context of the already published literature.

We thank the reviewer for the efforts to review our paper. As suggested, we included an overview table of the gross land use change implementations in current DGVMs. The introduction, model description and discussion sections are revised to take into account the existing work, and to make our implementation more relevant with other DGVMs. In addition, the whole manuscript has been carefully checked to avoid minor editing errors such as those raised by the reviewer in the technical comments.

In particular:

1. Regarding the effects of net vs. gross transitions, there has been a recent multimodel study by Arneth et al. (2017) that showed the importance of tree harvesting and land clearing from shifting cultivation. In this paper seven models were used to determine the influence of wood harvest and shifting cultivation. It might be helpful to relate to the findings of Arneth et al. (2017).

The work of Arneth et al. (2017) has been included in the discussion in our paper. Their work is now cited in the introduction as well in the revised manuscript. In both sections of introduction and discussion, references to this work are expanded.

2. The described approach to model gross transitions as matrices looks very similar to the implementation of gross transitions in the DGVM JSBACH, as described by Reick et al. (2013), which has not been mentioned at all in the manuscript so far (please also see the comment on the lines 87-93 below). It would be helpful to include some comparisons of the way Yue et al. represent gross transitions and the way it is presented in Reick et al. (2013). The same might hold for the mentioned paper describing LPX-Bern (Stocker et al., 2014). There are two further models listed in the 2015 update on the global carbon budget that include gross transitions (Table 5; Le Quere et al., 2015): CLM4.5 (Oleson et al., 2013) and VisIt (Kato et al., 2013), which might also be worth looking at.

The similarity between Reick et al. (2013) and our work is that both are based on LUHv1 data and include gross transitions. There are two major differences: (1) Reich et al. (2013) focused on

reconciling dynamic vegetation process and external forcing data, while in our paper the dynamic vegetation is turned off and we relied on reconstructed historical land cover time series that are made consistent with the model. (2) Reick et al. (2013) made it an internal JSBACH model decision process on how to convert LUHv1 land cover types (i.e., primary and secondary natural lands) into model plant functional types (i.e., forest versus grassland, the pasture rule etc.). Whereas we focus on including different aged land cohorts in the ORCHIDEE model and implementing a set of hierarchical rules regarding the land cohorts subjected to different land use change processes. The allocation of natural lands into forest versus grasslands, and the reconciliation of LUHv1 land cover distributions and the current-day satellite-based PFT map, instead, are handled independently by external preparations of reconstructed historical PFT map time series. These differences are now discussed in the revised text where they're relevant. We added in following texts in Sect. 2.1.4 : *“This is different from the LUC implementation in JSBACH DGVM in Reick et al. (2013) where a lot efforts have been devoted to reconciling the vegetation types in the forcing data (primary and secondary natural lands in the Land Use Harmonized data set version 1 or LUH1 data) and the vegetation distributions simulated by the dynamic vegetation module of JSBACH. We focus on including sub-grid land cohorts in the model and implementing a set of hierarchical rules on which land cohorts are subjected to different LUC processes (Table 2). The allocation of natural lands into forest versus grasslands in the model, and the reconciliation of LUH1 land cover distribution and model PFT map, instead, are handled by independent preparations of reconstructed historical land cover map time series.”*

We also included references to other models as mentioned by the reviewer. In response to Benjamin Stocker's comments on a companion paper of the current study (bg-2017-39, Biogeosciences Discussions), we added an overview table of current DGVMs with implementations of gross land use change (Table 1 in revised text). For CLM4.5, we contacted Peter Lawrence and Danica Lombardozzi (personal communications) and they confirm that gross land use change has not yet been included in CLM4.5 but will be included in CLM5.

3. There are several DGVMs that have some kind of age structure, e.g. LPJ-Guess with its gap dynamics (Smith et al., 2014) and LM3V (Shevliakova et al., 2009). The latter is particularly interesting for the manuscript of Yue et al. because of the combination of simulated secondary regrowth and land use and land management, including shifting cultivation.

We thank the reviewer for referring to these highly relevant works. They're now cited and discussed in the revised paper in the introduction and discussion sections.

4. I do not understand which of the implementations regarding age structure stem from ORCHIDEE-CAN and which are newly developed in this study (l. 190-221), and I think it would be helpful if the authors could revisit this paragraph for clarity. Particularly, I do not understand how cohorts are ageing in ORCHIDEE-MICT. Since this might be a critical aspect for the described carbon dynamics it would be helpful if the authors could put some more emphasis in describing the ageing of the forest, maybe an additional Figure could help.

The basic approach and code base to introducing sub-grid cohorts are brought from previous developments in ORCHIDEE-CAN, which was made with the purpose to represent sub-grid forests of different age classes. This is stated in the original manuscript (line 205–206). To make

this clearer, we inserted the following sentence after the original line 206: *“The code base to include sub-grid forest cohorts are migrated from ORCHIDEE-CAN, with substantial adaptations being made in ORCHIDEE-MICT. Except for this, all other LUC developments have been achieved within the current study.”* As ORCHIDEE-MICT is based on a single-leaf model, the aging of cohorts is simply represented by moving the concerned cohort to the next (older) one when its wood mass exceeds the cohort upper boundary. Except for cohort boundary, no further cohort-specific parameterization is done, so essentially all cohorts are governed by the same set of biophysical and ecological parameter values. However, in ORCHIDEE-MICT there do exist some “aging” processes to approximate some key changes when a forest ages, notably, the NPP allocation to belowground sapwood decreases with the time since establishment, that is, more biomass is allocated belowground to develop roots for young trees. We inserted the following sentences at the end of the 3rd paragraph in Sect. 2.1.3 to clarify this: *“Forest grows old by moving from the current cohort to the next one when the woody biomass exceeds the cohort upper boundary. Except for the cohort boundaries, no further cohort-specific parameterizations have been done, so essentially all cohorts are governed by the same set of biophysical and ecological parameter values. However, in ORCHIDEE-MICT there are indeed some simple “aging” processes to approximate the key changes when a forest grows old, notably, the NPP allocation to belowground sapwood decreases with the time since establishment.”* We don’t think an additional figure is needed so it is not provided.

lines 87-93: This paragraph is unfortunately not correct. Gross transitions are implemented in the DGVM JSBACH (see Reick et al., 2013), not in an emulator. Also, Wilkenskjeld et al. (2014) did not use an emulator but the carbon cycle sub-module of JSBACH, for efficient comparisons of net and gross transitions. Furthermore, JSBACH with gross transitions has already been used in the MPIESM simulations for CMIP5 and in TRENDYv4 simulations used in the global carbon budget in 2015 (Le Quere et al., 2015). In this budget, two further models beside JSBACH did include gross transitions (see "shifting cultivation", Table 5, Le Quere et al., 2015). The reason why no model included gross transitions in the 2016 update of the global carbon budget was because the LUH2v2h data set was not ready: "The more comprehensive harmonised land-use data set (Hurtt et al., 2011), which also includes fractional data on primary vegetation and secondary vegetation, as well as all underlying transitions between land-use states, has not been made available yet for this year. Hence, the reduced ensemble of DGVMs that can simulate the LUC flux from the HYDE data set only." (Le Quere et al., 2016).

Thanks for the reviewer for pointing out this mistake. It is now corrected. We added an overview table for DGVMs that have implemented gross land use changes (Table 1 in the revised manuscript).

line 115: "sub-grid sub-grid"

done.

line 113: "plant function types" -> plant functional types

done.

line 137: "forgings" -> forcings

done.

lines 215-217: this assumption might not be correct for natural grasslands and pastures (see e.g. Nyawira et al. 2016 and references therein).

We agree with the reviewer that our parameterization of herbaceous MTCs in terms of soil carbon changes cannot accommodate changes of SOC in all different LUC types. The effectiveness of this feature of differentiating herbaceous MTCs is limited by the model's simulation of soil temperature and moisture and the computation efficiency (as is explained in the original text, line 481–486). Therefore, this feature is more for informative purpose and serves as a “place holder” for the future improvement in this scheme, rather than having solid scientific significance. We added in the revised two blocks of texts to clarify these points. We inserted the following texts in the 4th paragraph of Sect. 2.1.2: *“Because the directional change of soil carbon largely depends on the vegetation types before and after LUC and climate conditions (Don et al., 2011; Poepplau et al., 2011), ideally agricultural cohorts from different origins should be differentiated. However, to avoid exploding the total number of cohorts and the associated computation demand, as a first attempt, we simply divide each herbaceous MTC into two broad sub-grid cohorts according to their soil carbon stocks and without considering their origins. We expect that such a parameterization can accommodate some typical LUC processes, such as the conversion of forest to cropland where soil carbon usually decreases with time, but not all LUC types (for instance, soil carbon stock increases when a forest is converted to a pasture).”*. We inserted in the last paragraph of Sect. 2.2.3 the following texts: *“Overall, this feature of separating herbaceous MTCs into multiple cohorts is coded more as a “place holder” for the current stage of model development rather than having solid scientific significance. To fully track soil carbon stocks of different vegetation types and their transient changes following land use change, a much larger number of cohorts are needed. But for a global application, this is limited by the computation efficiency.”*

line 285: "The cohort age subject to LUC of is one..." -> remove the of

done.

line 328: According to their webpage (http://gsweb1vh2.umd.edu/luh_data/LUHa.v1/readme.txt) LUH1 also makes a distinction of harvest from mature and young forest. Do you use this information in your model, too? Furthermore, LUH contains "harvest from non-forested land", is this information used?

We treat harvest from mature forest in LUH1 as primary forest harvest, and this has already been explained in section 2.1.4 in the original manuscript (line 336). Harvest from young forest in LUH1 is implemented as secondary forest harvest (also see details in the same paragraph. “Harvest from non-forest land” is not included in our analysis. We inserted the following sentence in the 2nd paragraph of Sect. 2.2.3 to clarify this: *“Wood harvest from primary and secondary forests in LUH1 is used, while wood harvest from non-forest is not.”*

line 341: "first go first for" -> first go for

done.

line 347: should this maybe be secondary?

We indeed mean “primary harvest” here.

line 359: "to ensure the their" -> to ensure that their?

We changed “the” to “their”.

line 386: but it respire in the grid cell where it is harvested?

Yes. Spatial relocation of harvested crops is not considered in the model. This point is now explained in the revised manuscript. We add the following sentence in Sect. 2.1.5: “*Agricultural harvest and associated fluxes to the atmosphere through food consumption or livestock feeding are assumed to happen locally in the model during the same year of harvest, without considering spatial relocation through international trade.*”

line 403: I do not understand this sentence

We apologize for this confusion. This sentence is changed to “ F_{Pasture} for carbon sources from pastures other than harvest”.

line 427: remove the "and"?

done.

line 430: replace "on" with "by"?

done.

line 445: held constant or held as constants

It should be “held constant”, now changed.

line 447: a hypothetical scenario

done.

line 448: I do not understand the sentence "Forest harvest of the same intensity..."

We mean “forest harvest of the same annual areal fraction”. This is revised.

lines 556-561: But why is the NPP in simulations with age dynamics smaller? Is the forest in these simulations not yet as productive than intermediate-age forest?

For this particular case NPP is smaller with age dynamics, but the global run shows NPP with age dynamics is higher, in principle due to lower autotrophic respiration (because of slightly lower biomass) in the simulation with age dynamics. In general, as ORCHIDEE-MICT uses a big-leaf approximation that allows LAI to quickly level out and NPP reaching its maximum, and because cohort woody mass boundaries are the only parameter that differ among forest cohorts, we expect

such differences in NPP between S_{age} and $S_{ageless}$ to be subtle and do not have significant scientific implications in the ecological process. The difference in simulated E_{LUC} is dominated by the difference in the forest biomass density being cleared. Therefore, the small differences in NPP between S_{age} and $S_{ageless}$ have not been explored in depth.

line 702: Do you mean Hurtt et al. 2006? Else the reference is missing.

We mean Hurtt et al., 2006 and we apologize for this typo. Now this reference is removed and we used exclusively Hurtt et al. 2011.

lines 710-715: It might be helpful to mention here again that LUH does include biomass harvest but that this is not used in your model.

This has been added.

line 748 this is section 6

This has been corrected.

line 753 and this section 7

This has been corrected.

line 1015: Fig. 9 does not include a "panel b"

This has been corrected.

1 **Representing anthropogenic gross land use change, wood harvest and forest** 2 **age dynamics in a global vegetation model ORCHIDEE-MICT v8.4.2**

3
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17 **Abstract**

18 Land use change (LUC) is among the main anthropogenic disturbances in the global carbon cycle. Here
19 we present the model developments in a global dynamic vegetation model ORCHIDEE-MICT v8.4.2 for
20 a more realistic representation of LUC processes. First, we included gross land use change (primarily
21 shifting cultivation) and forest wood harvest in addition to net land use change. Second, we included sub-
22 grid even-aged land cohorts to represent secondary forests and to keep track of the transient stage of
23 agricultural lands since LUC. Combination of these two features allows simulating shifting cultivation
24 with a rotation length involving mainly secondary forests instead of primary ones. **Furthermore, a set of**
25 **decision rules regarding the land cohorts to be targeted in different LUC processes have been**
26 **implemented. Idealized site-scale simulation has been performed for miombo woodlands in**
27 **Southern Africa assuming an annual land turnover rate of 5% grid cell area between forest and**
28 **cropland. The result shows that the model can correctly represent forest recovery and cohorts**
29 **aging arising from agricultural abandonment. Such a land turnover process, even though without a**
30 **net change in land cover, yields carbon emissions largely due to the imbalance between the fast**
31 **release from forest clearing and the slow uptake from agricultural abandonment. The simulation**
32 **with sub-grid land cohorts gives lower emissions than without, mainly because the cleared**
33

34 secondary forests have a lower biomass carbon stock than the mature forests that are otherwise
35 cleared when sub-grid land cohorts are not considered. Over the region of Southern Africa, the
36 model is able to account for changes in different forest cohort areas along with the historical
37 changes in different LUC activities, including regrowth of old forests when LUC area decreases.

38 Our developments provide possibilities to account for continental or global forest demographic change
39 resulting from past anthropogenic and natural disturbances.

40

41 Keywords: dynamic vegetation model, gross land use change, age dynamics, shifting cultivation, wood
42 harvest, land use emissions

43

44 1 Introduction

45 Land use and land use change (LUC) strongly modifies the properties of the Earth's surface, ecosystem
46 services and the carbon and nutrient fluxes between the land and the atmosphere. These activities have
47 significant impacts on the Earth's climate through both biogeochemical and biophysical effects (Foley et
48 al., 2005; Luysaert et al., 2014; Mahmood et al., 2014). When a forest is cleared, the majority of carbon
49 stored in the aboveground biomass is lost as CO₂ to the atmosphere. Such loss can occur within a few
50 years if fire is used in deforestation (Morton et al., 2008), or more slowly through decomposition of the
51 slash left on the ground (Houghton, 1999). Various products made from harvested wood, though, often
52 take a few decades to degrade and return the carbon to the atmosphere (Mason Earles et al., 2012). In
53 addition, LUC changes the balance between litter input and heterotrophic respiration, resulting in changes
54 in soil organic carbon (SOC) (Don et al., 2011; Guo and Gifford, 2002; Poeplau et al., 2011; Powers et
55 al., 2011).

56

57 Globally, LUC activities have contributed significantly to historical anthropogenic carbon emissions. It is
58 estimated that about 800 Mha (1Mha = 10⁶ha) of forests were cleared for agricultural purpose and that
59 2000 Mha of forests were harvested during 1850–1999, giving rise to cumulative emissions of 124 Pg C,
60 or 33% of the total anthropogenic emissions (Houghton, 1999). Houghton et al. (2012) reviewed LUC
61 emissions from multiple studies and estimated the annual global LUC emissions as 1.1 Pg C yr⁻¹ during
62 1980–2009, with an uncertainty of 0.5 Pg C yr⁻¹. Different estimations of historical LUC emissions by
63 Dynamic Global Vegetation Models (DGVM) show a spread as large as 1 Pg C yr⁻¹ (see Fig. 1 in
64 Houghton et al. 2012; see also Hansis et al. 2015 for an even larger range among model estimations). This
65 is partly due to different forcing data used and initial carbon stocks simulated (Li et al., 2017), but also
66 because of different implementations of LUC processes in dynamic global vegetation models (Prestele et

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Supprimé: Though the directions of SOC change are roughly consistent among typical LUC transitions (e.g., SOC decreases when a forest is converted to cropland; SOC increases when a cropland is converted to pasture), large uncertainties remain regarding the magnitude of SOC changes and its relationship with secondary ecosystem management, climate, soil physical and biogeochemical properties, and the time elapsed since LUC.

77 al., 2016). **Given the importance of understanding historical LUC emissions in projecting the future**
78 **land-based mitigation potential, a more realistic representation of LUC processes and land**
79 **management in DGVMs is desirable.**

80
81 In most global studies, only net transitions were accounted for in the LUC processes simulated by
82 DGVMs (Le Quéré et al., 2015). Changes in land use over each model grid cell are diagnosed as the
83 difference in ground fractions of different land cover types between two consecutive years. At a typical
84 spatial resolution of 0.5° for global applications (e.g., TRENDY, Sitch et al., 2015; MsTMIP,
85 http://nacp.ornl.gov/MsTMIP_simulations.shtml), such a scheme has ignored the simultaneous, bi-
86 directional transitions between two vegetation types within the same grid cell (i.e., gross transitions).
87 **Such gross transitions can arise from spatial upscaling of land use change data, or from certain**
88 **land use activities. A typical example is shifting cultivation, a form of smallholder subsistence**
89 **agriculture primarily occurring in tropical regions that involves clearing a forest for a non-**
90 **permanent agricultural land, which is often abandoned later. Shifting cultivation was historically**
91 **important in many tropical regions for the subsistence of indigenous people (Hurt et al., 2011;**
92 **Lanly, 1985) although more recently it has been in the process of being superseded by more**
93 **intensified land management (Heinimann et al., 2017). Forest management such as a clear-cut for**
94 **wood harvest followed by replanting trees is another type of gross transition. Although it does not**
95 **entail any net change in land cover (forest remaining forest), species choice and forest management**
96 **can have a significant effect on carbon stocks and fluxes (Erb et al., 2017).**

97
98 **More and more DGVMs started to include gross transitions and we provide an overview of them in**
99 **Table 1. All models in Table 1 include shifting cultivation and wood harvest except that shifting**
100 **cultivation is not included in ISAM, and five of them include sub-grid secondary land tiles when**
101 **accounting for land use change. A recent review by Arneeth et al. (2017) found that including**
102 **processes that have been previously neglected in DGVMs, including gross transitions and other**
103 **land management processes such as crop harvest and management, can lead to an upward shift of**
104 **estimated LUC emissions. Their study thus highlights the importance of including these processes.**
105 **Furthermore, to more robustly account for shifting cultivation and wood harvest, which often have**
106 **a certain rotation length and mainly involve secondary forests of different ages, it is critical for**
107 **DGVMs to include sub-grid differently aged land cohorts. This feature exists in some DGVMs that**
108 **combine with a forest gap model (e.g., LPJ-GUESS, Bayer et al., 2017) but it would be difficult to**
109 **represent forest species change because different tree plant functional types are mixed over a model**
110 **grid cell. The same also applies for LM3V (Shevliakova et al., 2009). Other so-called area-based**

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Supprimé: This will help improve the diagnostic of the current global carbon cycle perturbation and better forecast its future evolution, which is useful for formulating efficient land-based climate mitigation strategies.

117 DGVMs (Smith et al., 2001) such as ISAM (Jain et al., 2013) and LPX-Bern 1.0 (Stocker et al.,
118 2014) included secondary land tiles in the model but their capability to represent different rotation
119 lengths in land use is limited. In the ORCHIDEE model, sub-grid forest cohorts have been recently
120 included in the ORCHIDEE-CAN branch mainly for forest management purposes (Naudts et al.,
121 2015), but to combine both sub-grid land demography and gross land transition is still missing.
122

123 Here we present the new model developments in ORCHIDEE that combines both sub-grid land cohorts
124 and gross land use change. The objectives of this study are: (1) to document a new LUC module,
125 including sub-grid vegetation cohorts, forest harvest and gross land use change in the ORCHIDEE model,
126 that can be run with and without sub-grid age dynamics; (2) to document through an idealized pixel
127 simulation the simulated carbon fluxes from shifting cultivation or land turnover between model
128 set-ups with and without sub-grid age dynamics; and (3) to document the model behaviour and
129 forest age dynamics associated with the historical changes in LUC activities. Whereas the current
130 manuscript focuses on documenting new model developments and subsequent changes in model
131 behaviour, a companion paper presents a global re-analysis of historical LUC emissions (Yue et al.,
132 2017).

133 2 Methods

134 2.1 Model developments to include sub-grid vegetation cohorts and gross transitions

135 2.1.1 Original land use change module with net transitions only

136 The model version as the starting point for our development is ORCHIDEE-MICT (r3247), a branch of
137 the ORCHIDEE DGVM (the major version is called the trunk version), the land surface component of
138 the French IPSL Earth System Model (ESM). ORCHIDEE can simulate the energy, water and carbon
139 fluxes between the land surface and the atmosphere. The carbon module simulates vegetation carbon
140 cycle processes, including photosynthesis, photosynthates allocation, vegetation mortality and
141 recruitment, phenology, litter fall and soil carbon decomposition. ORCHIDEE-MICT is a branch initially
142 focusing on improving high-latitude processes (e.g., soil freezing, snow processes, permafrost dynamics
143 and northern wetlands) but is now under development to include more processes. Of interest for this study
144 is that the grassland management module developed in Chang et al. (2013) is included (r2615). This
145 allows for distinction between natural grassland and pasture that have been mixed together in previous
146 LUC simulations by ORCHIDEE.

147
148 In ORCHIDEE, land cover types are represented as plant functional types (PFTs), with each PFT being
149 associated with a set of parameters. A typical model simulation consists of two stages: a spin-up stage

150 with stable or constant forcing data until the model reaches an approximately equilibrium state, to mimic
151 an era with no appreciable human perturbation, and a transient stage, where the model is forced with
152 temporally varying forcings (e.g., climate, atmospheric CO₂, land cover etc.). The land use change
153 module prior to this study accounts for net transitions only (Piao et al., 2009a) and has been used in many
154 applications (e.g., CMIP5, <http://icmc.ipsl.fr/index.php/cmip5>; TRENDY, Sitch et al., 2015). To simulate
155 historical land use change, a spin-up run is initiated with a given initial land cover map (i.e., a PFT map),
156 and then vegetation distribution is updated annually with prescribed PFT map time series during the
157 transient simulation. The LUC module simply compares grid cell fractions of different PFTs between the
158 current simulation year and the next year. Then twelve vegetative PFTs (all standard model PFTs
159 excluding the bare soil PFT) are separated into two groups with expanding versus contracting areas.
160 Carbon stocks and associated carbon fluxes on shrinking PFTs are displaced to expanding PFTs in
161 proportion to their respective surface increments.

162 **2.1.2 Concept of gross transitions in relation to vegetation age structure**

163 The numerical implementation of net transitions is straightforward. However, as explained in the
164 introduction, this scheme omits important sub-grid gross land use transitions. Figure 1 uses an exemplary
165 grid cell to illustrate the difference between the two LUC schemes: one accounting for net transitions only
166 (Fig. 1b), and the other accounting for gross transitions but with no sub-grid cohorts (Fig. 1c & 1d).
167 Although the areas of forest and cropland after LUC are identical (Fig. 1b & 1d), carbon stocks for the
168 same vegetation type (e.g., forest) are different between the two schemes. According to the net transition
169 scheme, the carbon stock of the final forest patch shown in Fig. 1b remains intact. But under the gross
170 scheme (Fig. 1d), the post-LUC forest carbon stock is an area-weighted mean between the original forest
171 patch not being impacted by LUC, and the newly established forest with a low carbon density that results
172 from cropland abandonment. Consequently the carbon stock of the grid cell is expected to be smaller in
173 Fig. 1d than in 1b and LUC carbon emission in Fig. 1d is conversely larger than in 1b.

174
175 Figure 1c represents the real land cover state after LUC, while the merging shown in Fig. 1d is only a
176 necessary simplification when no sub-grid cohorts are represented in the model. Ideally, the model
177 capability could be expanded to include cohorts, to represent the real world case as in Fig. 1c. In addition,
178 inclusion of sub-grid cohorts would allow not only the distinction between original intact forest and
179 newly established forest, but also allow distinguishing among different forest cohorts (e.g., primary
180 versus secondary forests) regarding which forest patch to be cleared for cropland.

181
182 Figure 2 illustrates a case where gross LUC is combined with sub-grid cohort representation in the model.
183 Here, multiple patches within a grid cell are used to represent cohorts of a single vegetation type but with

184 different ages since establishment. These cohorts often have different carbon stocks either due to different
185 lengths in carbon accumulation time (e.g., for forest) or due to different extents to which legacy soil
186 carbon is present (e.g., for croplands establishing on former forests). The areas subject to gross LUC
187 transition in Fig. 2a & 2b remain the same as in Fig. 1a (dashed red rectangles), but primary and
188 secondary forests are cleared in Fig. 2a and Fig. 2b, respectively. Thus LUC emissions from clearing of
189 primary forest are expected to be higher due to its higher biomass stock. Correspondingly, the legacy soil
190 carbon stocks on the cohort of new cropland are also higher (shown in Fig. 2b & 2d).

191

192 Figure 1 and Fig. 2 have shown the example of LUC transitions between forest and cropland, but other
193 types of land use changes, including forest harvest, can be handled in a similar way. In the case of forest
194 harvest, having cohorts avoids the simplification to merge a young re-established forest after harvest with
195 the original forest, which serves as the exact source of harvest. This can effectively simulate forest
196 management practices that induce rotations of different forest cohorts (e.g., see McGrath et al., 2015 for a
197 forest management history in Europe).

198 2.1.3 Expansion of ORCHIDEE-MICT capacity to represent sub-grid vegetation cohorts

199 In order to simulate gross LUC combined with sub-grid vegetation cohorts as illustrated in Fig. 2, we
200 expanded the ORCHIDEE-MICT capability to include sub-grid even-aged cohorts. This necessitates
201 multiple patches within a grid cell for a single PFT, which inherit most of the parameters from their
202 parent PFT (they still belong to the same PFT and thus are largely physically similar). These patches are
203 named here *Cohort Functional Types (CFT)*, to be distinguished from the original *plant functional types*.
204 In this sense, the original PFTs actually become “meta-PFTs” which were named meta-classes (MTCs).
205 As subsequent land use changes generate differently aged CFTs, the computational demand will be
206 greatly increased. Hence, the number of CFTs within an MTC is limited to a user-defined number.

207

208 ORCHIDEE-trunk has a feature called “PFT externalization” which allows creating a user-specified new
209 PFT by inheriting its parameters from an existing one. A user can then modify specific parameters at their
210 convenience. Based on this feature, the ORCHIDEE-CAN branch (svn rev. = r2566; Naudts et al., 2015,
211 Page 2037) has developed representation of sub-grid forest age classes (i.e., equivalent to our CFTs here).
212 Each forest age class is an inheritance of a given forest MTC. There, the transitions from one age class to
213 another were defined by tree diameters. When a forest of a certain age class reaches its diameter limit, it
214 moves into the next age class, and is merged with the existing forest patch of that age class if there is one.
215 All associated biophysical and biogeochemical variables are merged as well following an area-weighted
216 mean approach with a few exceptions for discrete variables such as the applied forest management
217 strategy.

218

219 ORCHIDEE-MICT also inherits this “externalization” feature from ORCHIDEE-trunk. **Here we ported**
220 **the codes of forest age class functionality from ORCHIDEE-CAN to develop the CFT functionality**
221 **needed for LUC simulation with cohorts in ORCHIDEE-MICT. The code base to include sub-grid**
222 **forest cohorts were migrated from ORCHIDEE-CAN, with substantial adaptations being made in**
223 **ORCHIDEE-MICT. Except for this, all other LUC developments have been achieved within the**
224 **current study.** Contrary to ORCHIDEE-CAN (see above), ORCHIDEE-MICT uses woody biomass to
225 delimit different forest cohorts, with older cohorts having a higher woody biomass. **Forest grows old by**
226 **moving from the current cohort to the next one when the woody biomass exceeds the cohort upper**
227 **boundary. Except for the cohort boundaries, no further cohort-specific parameterizations have**
228 **been done, so essentially all cohorts are governed by the same set of biophysical and ecological**
229 **parameter values. However, in ORCHIDEE-MICT there are indeed some simple “aging” processes**
230 **to approximate the key changes when a forest grows old, notably, the NPP allocation to belowground**
231 **sapwood decreases with the time since establishment.**

232

233 In addition, we expanded the concept of CFT to croplands, natural grasslands and pastures. Cohorts are
234 defined with their soil carbon stocks for these herbaceous vegetation types; this is a definition relevant to
235 LUC emission calculation. **Because the directional change of soil carbon largely depends on the**
236 **vegetation types before and after LUC and on climate conditions (Don et al., 2011; Pooplau et al.,**
237 **2011), ideally agricultural cohorts from different origins should be differentiated. However, to**
238 **avoid inflating the total number of cohorts and the associated computation demand, as a first**
239 **attempt, we simply divide each herbaceous MTC into two broad sub-grid cohorts according to their**
240 **soil carbon stocks and without considering their individual origins. We expect that such a**
241 **parameterization can accommodate some typical LUC processes, such as the conversion of forest to**
242 **cropland where soil carbon usually decreases with time, but not all LUC types (for instance, soil**
243 **carbon stock increases when a forest is converted to a pasture).** The biomass or soil carbon thresholds
244 that delineate different CFTs must be properly parameterized in order to have sensible CFT segregation
245 within different contexts of land use change. **This will be further detailed in the Sect 2.2.3.** In practice,
246 for single-site simulations, the parameterization could be set up via a configuration file enumerating the
247 thresholds for all CFTs. For regional applications, an input file containing spatially explicit thresholds
248 will be used.

249

250 The implementation of sub-grid cohort function types as inheritances of meta-classes and the
251 corresponding hierarchy are exhibited in Fig. 3a. “Tier 1” of the “*Model parameterization hierarchy*”

252 corresponds to the four basic vegetation types (forest, natural grassland, pasture, and croplands,
253 abbreviated as f , g , p , c respectively). “Tier 2” corresponds to meta-classes in ORCHIDEE-MICT, which
254 contain one bare soil MTC and fourteen vegetative MTCs, with each vegetative MTC belonging to one of
255 the four basic vegetation types. “Tier 3” corresponds to cohort function types. A cohort functional type is
256 noted as CFT_{ij} to denote that it inherits its parameter values from the MTC_i and belongs to the j^{th} cohort.
257 For this study, forest MTCs contain six CFTs and herbaceous MTCs contain two CFTs. The number of
258 CFTs for each MTC is not hard-coded in the model and can be specified by users via a configuration file.

259

260 With sub-grid cohorts, the model spin-up run is initiated with an input MTC map, essentially the same as
261 in the case without sub-grid cohorts (recall that in Sect. 2.1.1 this MTC map is called a PFT map). But the
262 difference is that the initial prescribed areas (as fractions of grid cell area) of different MTCs are all
263 assigned to their youngest cohorts. During model spin-up forest woody mass will grow to exceed the
264 thresholds of the first cohort, so that forests will move to the second cohort, and so on. At the end of spin-
265 up, all forests thus end up in the oldest cohort of each MTC. The same case applies to herbaceous MTCs,
266 given that cohort thresholds are properly defined (see more details in Sect. 2.2.3).

267

268 **Natural forest mortality in ORCHIDEE could be either prescribed as a constant rate or**
269 **dynamically simulated, but in the case of prescribed vegetation cover, mortality takes effects by**
270 **reducing the amount of existing biomass only, with the coverage of the concerned forest patch being**
271 **unchanged. Likewise, recruitment increases forest individual density and update leaf age and other**
272 **relevant variables, but again, forest coverage remains unchanged. These features are necessary, as**
273 **the original ORCHIDEE model does not take into account forest demography. As explained in**
274 **Krinner et al. (2015, page 8), recruitment sapling biomass is only incorporated when the existing**
275 **biomasses is virtually zero while a larger-than-zero ground coverage is prescribed. These features**
276 **remain the same when sub-grid cohorts are used, i.e., forest mortality or recruitment does not**
277 **modify forest cohort ground coverage. In addition, forest mortality and subsequent regeneration**
278 **due to forest fires are handled in a similar manner.** ORCHIDEE-MICT has integrated a prognostic fire
279 module to simulate open grassland and forest fires arising from both natural and anthropogenic ignitions
280 (Yue et al., 2014). Other forest disturbances, such as wind-throw, diseases and insect outbreaks, are not
281 explicitly considered in ORCHIDEE-MICT. Because of these reasons, after the spin-up, the only way to
282 create secondary cohorts in the model is through land use change.

283

284 When entering transient simulations with land use change, younger cohorts will begin to be created. From
285 a modeling perspective, the oldest cohorts in ORCHIDEE-MICT are somewhat equivalent to the

286 primary lands (especially, the oldest forest cohorts are equivalent to primary forests), and other younger
287 cohorts are analogue to secondary lands.

288 **2.1.4 Model developments to include gross land use change and forest harvest, with and without** 289 **sub-grid cohorts**

290 This section describes the implementation of gross land use change and forest harvest with sub-grid
291 CFTs. We focus on the implementation with sub-grid cohorts, because the same LUC process without
292 cohorts could be simply treated as a particular case where all MTCs have only one single cohort. The
293 module interface is designed to receive forcing information on land area fluxes among four basic land
294 cover types of forest (*f*), natural grassland (*g*), pasture (*p*) and cropland (*c*), taking into account the current
295 LUC modeling landscape in DGVMs (as briefly reviewed in the Introduction) and the availability of land-
296 use change reconstructions (e.g., Hurtt et al., 2011). The present developments are intended for the case
297 where changes in vegetation coverage are only driven by historical LUC activities and so there is no need
298 to use the dynamic vegetation module of ORCHIDEE. **This is different from the LUC implementation**
299 **in JSBACH DGVM in Reick et al. (2013) where a lot efforts have been devoted to reconciling the**
300 **vegetation types in the forcing data (primary and secondary natural lands in the Land Use**
301 **Harmonized data set version 1 or LUH1 data) and the vegetation distributions simulated by the**
302 **dynamic vegetation module of JSBACH. We focus on including sub-grid land cohorts in the model**
303 **and implementing a set of hierarchical rules on which land cohorts are subjected to different LUC**
304 **processes (Table 2). The allocation of natural lands into forest versus grasslands in the model, and**
305 **the reconciliation of LUH1 land cover distribution and model PFT map, instead, are handled by**
306 **independent preparations of reconstructed historical land cover map time series.**

307
308 In order to compare the simulation results from the gross LUC module with the original net-transition-
309 only LUC module, we separate the gross LUC areas into two additive terms: ‘net change’ equivalent to
310 the original net transition (prescribed by the matrix M_{net}), and ‘land turnover’ for the bi-directional equal
311 land fluxes between any pair of land cover types (prescribed by the matrix M_{turnover}). Similarly, the forest
312 harvest information is prescribed in a third matrix M_{harvest} . For the moment, information for all the three
313 LUC types is provided as fraction of grid cell area. This is a deliberate choice, mainly for the convenience
314 of progressive stage-wise model development. We will come back to the influence of this choice within
315 the land use decision contexts in the Discussion section.

316
317 The key processes of the gross LUC module with CFTs are shown in Fig. 4, comprising in total 6 steps.
318 The LUC module is called at the first day of each year. Input data are the three matrices. M_{net} and M_{turnover}
319 are both square matrices with a size of 4 by 4:

$$\mathbf{M}_{\text{net}} (\mathbf{M}_{\text{turnover}}) = \begin{array}{c} \text{Donating land type} \\ \left[\begin{array}{c} \text{forest} \\ \text{grassland} \\ \text{pasture} \\ \text{cropland} \end{array} \right] \begin{array}{c} \text{Receiving land type} \\ \left[\begin{array}{cccc} \text{forest} & \text{grassland} & \text{pasture} & \text{cropland} \\ F_{f \triangleright f} & F_{f \triangleright g} & F_{f \triangleright p} & F_{f \triangleright c} \\ F_{g \triangleright f} & F_{g \triangleright g} & F_{g \triangleright p} & F_{g \triangleright c} \\ F_{p \triangleright f} & F_{p \triangleright g} & F_{p \triangleright p} & F_{p \triangleright c} \\ F_{c \triangleright f} & F_{c \triangleright g} & F_{c \triangleright p} & F_{c \triangleright c} \end{array} \right] \end{array} \right]$$

Eq (1)

320

321 Where the element $F_{i \triangleright j}$ denotes the land flux from land cover type i to j , with i, j being elements of the

322 vector of $[f \ g \ p \ c]^T$. The diagonal elements correspond to land fractions intact from any land use

323 transitions and are simply ignored in the LUC module. By definition, $\mathbf{M}_{\text{turnover}}$ is a symmetric square

324 matrix. $\mathbf{M}_{\text{harvest}}$ is a matrix with only two elements: harvest area from primary and secondary forests.

325

326 As explained in Sect. 2.1.3, the construction of CFTs within the model follows the “model

327 parameterization hierarchy” shown in Fig. 3a. The cohort age subjected to LUC is one of the most

328 important considerations in land use change decisions, especially in the context of land turnover and

329 forest harvest. This necessitates a re-organization of the CFTs to derive the “LUC hierarchy” shown in

330 Fig. 3b, where Tier 2 information is about areas of different cohorts of the same land cover type, and Tier

331 3 remains on the level of CFTs. So the Step 1 in the LUC module (Fig. 4) is to construct the “LUC

332 hierarchy”, i.e., to calculate within the model the areas of each cohort for each vegetation type.

333

334 When implementing LUC matrices, all information of land transitions between the four basic land cover

335 types must first be downscaled on the cohort tier (i.e., decision on which cohort is subjected to LUC) and

336 then on the CFT tier (i.e., how LUC-affected area is distributed among different comprising meta-classes

337 within each cohort, refer also to Fig. 3b). This is achieved in Step 2 as shown in Fig. 4. Because all the

338 newly established lands, regardless of their originating LUC process, must belong to the youngest CFT of

339 the MTCs that comprise the target land cover type, the ultimate outcome of Step 2 is a single (large)

340 matrix $\mathbf{M}_{\text{nCFT, nMTC}}$ (nCFT = # of CFTs, nMTC = # of MTCs), which indicates the area transferred from

341 each CFT to the youngest cohort of the concerning MTC. The rules to convert LUC matrices into

342 components of $\mathbf{M}_{\text{nCFT, nMTC}}$ depend on LUC types and will be explained in detail later. But as long as Step

343 2 is done, the remaining steps are rather straightforward.

344

345 Step 3 handles forest wood collection (here ‘collection’ rather than ‘harvest’ is used, to avoid the

346 confusion with forest wood harvest which is a means of forest management), from forest being converted

347 to other land cover types, and forestry harvest (forest remaining forest). We assume that a certain fraction

348 of aboveground woody biomass (i.e., sapwood and heartwood) is lost as instant CO₂ flux into the
 349 atmosphere (i.e., due to on-site disturbance), and that the remaining wood is collected as wood product
 350 pools. Step 4 involves the proper displacement of associated carbon stocks and fluxes from the donating
 351 CFTs to the newly established (youngest) cohorts of MTCs, after wood collection. Notably, the legacy
 352 carbon stocks in litter and soil collected from the donating CFTs are transferred to the newly established
 353 youngest CFTs. Then in Step 5, each youngest CFT cohort is established and initialized, with its fraction
 354 of grid-cell area being the sum of contributing areas given by each source CFT. Finally, in Step 6, a newly
 355 established cohort is merged with the existing youngest CFT cohort if there is one. When merging stocks
 356 or fluxes between the newly established and existing CFTs, an area-weighted mean approach is followed:

$$357 \quad x_{merged} = \frac{x_{new} \times area_{new} + x_{existing} \times area_{existing}}{area_{new} + area_{existing}} \quad \text{Eq (2)}$$

358 Where x is the variable in question (e.g., leaf biomass, soil carbon stock etc.), x_{new} and $x_{existing}$ are the
 359 values of the newly established patch and the existing patch before merging, respectively, and x_{merged} is
 360 the value of the composite patch after merging. $area_{new}$ and $area_{existing}$ are patch areas of the newly
 361 established and the existing patch, respectively.

362
 363 We now return to Step 2, explaining the different rules used to build the $\mathbf{M}_{nCFT, nMTC}$ components for
 364 different LUC types. We start with $\mathbf{M}_{harvest}$ by assuming that it precedes conversion of forest to other land
 365 cover types (i.e., land turnover or net land use change). As is explained, the LUC module is designed to
 366 receive externally prescribed harvest information, especially from the widely used LUH1 reconstruction
 367 (Hurt et al., 2011), rather than to determine harvest volume internally within in the model. The LUH1
 368 distinguishes between harvests from primary and secondary forests and non-forest vegetation but in
 369 ORCHIDEE only harvest from forests is considered. The harvest information is provided as both forest
 370 area and harvested biomass in LUH1. Here we used the area information (a deliberate choice that will be
 371 discussed in Sect. 4). Because of this, ensuring the consistency between the harvest area in the forcing and
 372 that being actually realized in the model is an important consideration. Moreover, as we want to compare
 373 simulated LUC impacts between the two model configurations with and without sub-grid cohorts, it is
 374 necessary to ensure that exactly the same LUC area is realized in both configurations. This involves a set
 375 of decision rules to properly allocate the prescribed harvest area into different forest cohorts (Table 2).

376
 377 Implementation of primary forest harvest is straightforward: we always start with the oldest cohort and
 378 move sequentially downwards to younger ones if older cohorts are exhausted, until the prescribed harvest
 379 demand is fulfilled (Table 2). For secondary forest harvest, we start with intermediate-aged cohorts. But if
 380 the existing area of intermediate-aged cohorts is not sufficient to fulfill the prescribed harvest area, we are

381 left with two options to either search upwards for older cohorts or downwards for younger ones. We
382 decide to first go for upward searching and then for downward searching, if all cohorts older than the
383 intermediate age still cannot fulfill the prescribed harvest demand (Table 2). This rule allows potential
384 temporal changes in harvested area to be accommodated, as explained in Fig. 5. Under such a scheme, (1)
385 at the very beginning (after spin-up) and before the existence of any secondary forests, harvest will start
386 with the oldest cohort, i.e., corresponding to harvest of primary forests (sometimes, because of the
387 inconsistency between the input harvest information and existing forest cohort structure in the model,
388 “secondary” forest harvest could be prescribed for pixels where only primary forests exist in the model).
389 (2) If harvest area of secondary forests remains stable, then as soon as sufficient intermediate-aged
390 cohorts are created via conversion of primary forest to re-growing younger cohorts, a corresponding
391 stable rotation cycle would be maintained in the model as well. (3) If the harvest area increases, the
392 upward searching would allow additional harvest of primary forests (i.e., area subject to the stable
393 rotation is expanded). (4) If the harvest area decreases, the moving of cohorts from younger to older ones
394 independent of any LUC activities would allow restoring older cohorts — e.g. a consequence of
395 abandonment of forest management. (5) Finally, the downward searching for younger cohorts after
396 exhausting all other older cohorts is solely to ensure the consistency between prescribed input harvest
397 area and that actually realized in the model. Hence, this scheme is designed in order to faithfully
398 implement the prescribed harvest areas in the model with an explicit consideration of forest successional
399 states (i.e., primary or secondary). But when this is not possible because of inevitable mismatch between
400 the model and forcing data, harvest areas of primary and secondary forests could mutually compensate for
401 each other in the model, to ensure that their prescribed total harvest area remains realized.

402
403 A number of studies reported that fallow lengths for shifting cultivation could range from a few years to
404 more than 50 years depending on different regions, with the majority being 10–40 years (Bruun et al.,
405 2006; Mertz et al., 2008; Thrupp et al., 1997; van Vliet et al., 2012), and there is a tendency in reduction
406 of fallow lengths possibly because of increased population pressure (van Vliet et al., 2012). Hurtt et al.
407 (2011) assumed a mean residence time of 15 years for shifting cultivation for tropical regions in the
408 LUH1 reconstruction data. Based on these reports, we assume forest clearance for shifting cultivation to
409 occur primarily in secondary forests, and treat it similarly as secondary forest harvest when allocating the
410 prescribed LUC area into different cohorts (Table 2). The only difference is that the destination land
411 cover remains forest in the case of forest harvest but is agricultural land in the case of shifting cultivation.
412 For all other land transfers in shifting cultivation (e.g., pasture to forest), we start exclusively from the
413 oldest cohort and move downwards to younger ones (Table 2). For net land use change, priority is again
414 given to older cohorts followed by younger ones (Table 2).

415
416 Finally, we still need to downscale the LUC area in each cohort to its component CFTs. This is done by
417 allocating the LUC area in each cohort to its member CFTs in proportion to the existing area of each CFT.

418 **2.1.5 LUC processes that remain unchanged in the model**

419 ORCHIDEE simulates two wood product pools with a turnover length of 10 years and 100 years,
420 respectively. Fractions of aboveground woody biomass as instant on-site losses (F_{instant}), and entering into
421 the two wood product pools ($F_{10\text{yr}}$, $F_{100\text{yr}}$) follow the values in the original net-transition-only LUC scheme
422 (Piao et al., 2009a), as shown in Table 3. Other biomass compartments (i.e., leaves, fine roots, coarse
423 roots, fruits and reserve pool) are transferred to litter pools during forest harvest or deforestation. **Carbon**
424 **in the two wood product pools is then released into the atmosphere according to their respective**
425 **turnover time, and this flux contributes to the overall land carbon balance as a source term (see the**
426 **next section).**

427
428 Other processes relevant to LUC are left unchanged with the original model version. In particular, crop
429 harvest is applied to cropland CFTs with a fraction of 45% of biomass turnover being ‘harvested’ in the
430 model and exported outside the ecosystem (Piao et al., 2009a). Pasture CFTs are also harvested in the
431 same fashion. **Agricultural harvest and associated fluxes to the atmosphere through food**
432 **consumption or livestock feeding are assumed to happen locally in the model during the same year**
433 **of harvest, without considering spatial relocation through international trade.** Fires are simulated
434 with a prognostic module, but as explained in Sect. 2.1.3, fire disturbances do not lead to creation of
435 young cohorts, but only their carbon consequences (e.g., emissions, vegetation mortality, etc.) are
436 included.

437 **2.2 Simulation set-up**

438 **2.2.1 Definition of land-use change emissions (E_{LUC}) and carbon flux sign convention**

439 The land carbon balance simulated by ORCHIDEE-MICT v8.4.2 (i.e., net biome production or NBP),
440 when land use change is included, is defined as:

$$441 \text{NBP} = \text{NPP} + F_{\text{Inst}} + F_{\text{Wood}} + F_{\text{HR}} + F_{\text{Fire}} + F_{\text{AH}} + F_{\text{Pasture}} \quad \text{Eq (3)}$$

442
443
444 Where NPP is the net primary production, and all fluxes with “F” notation are outward carbon fluxes
445 from the land system (they are assigned a negative sign following the ecosystem convention, indicating
446 that carbon is lost from ecosystems), with F_{Inst} for the instantaneous carbon flux during LUC (e.g., carbon
447 release arising from site preparation, land-clearing burning etc.), F_{Wood} for the delayed carbon release due

448 to wood products degradation, F_{HR} for heterotrophic respiration from litter and soil organic carbon
449 decomposition, and F_{AH} for agricultural harvest on both croplands and pastures, and $F_{Pasture}$ for carbon
450 sources from pastures other than harvest, i.e., export of animal production and methane emissions (see
451 Chang et al., 2015 for details). **F_{Inst} and F_{Wood} are both fluxes on an annual time scale that depend
452 only on wood mass at the time of forest clearing and the respective wood product degradation rates
453 (see Sect. 2.1.5). F_{HR} is simulated at a time step of 30 minutes and depend on soil temperature and
454 moisture. F_{Fire} is simulated with a prognostic fire module SPITFIRE (Yue et al., 2015).**

455
456 The LUC emissions (E_{LUC}) are quantified as the difference in simulated NBP between two paired
457 simulations, with LUC (or a specific LUC process) included in one simulation but not the other one:

$$459 E_{LUC} = NBP_{LUC} - NBP_{control} \quad \text{Eq (4)}$$

460
461 Where, NBP_{LUC} and $NBP_{control}$ are NBP simulated with and without LUC. A negative E_{LUC} denotes a
462 carbon source to the atmosphere, i.e., ecosystem carbon sink is reduced because of land use change. This
463 definition follows Pongratz et al. (2014, Page 178) and is also the same as used in TRENDY (Sitch et al.,
464 2015) simulations and the existing global carbon budget analysis (Le Quéré et al., 2016). As explained by
465 Pongratz et al. (2014), such a definition quantifies the “net” LUC flux because it integrates both
466 emissions to the atmosphere (e.g., deforestation) and uptakes by potentially recovering vegetation (e.g.,
467 agricultural abandonment). More specifically, this corresponds to the definition “D3” using uncoupled
468 DGVM simulations in Pongratz et al. (2014, Eq. 15c, Page 187), which contains instantaneous fluxes,
469 legacy fluxes, and “loss of additional sink (source) capacity (LOAS)”.

470
471 Instantaneous fluxes refer to the carbon emissions directly arising from LUC, often occurring within the
472 first year since LUC (F_{Inst} in our case). Legacy fluxes arise from the readjustment of carbon stocks to the
473 new type of vegetation and/or the changes in management intensity over time (Pongratz et al., 2014), and
474 “loss of additional sink (source) capacity (LOAS)” refers to the carbon sink/source difference between the
475 actual land cover after LUC and the otherwise potential one under environmental perturbations. All other
476 flux terms on the right side of Eq. (3) except F_{Inst} contribute to the legacy fluxes and LOAS. Here, as our
477 model development mainly distinguishes the biomass carbon of secondary forests, it’s expected that F_{Inst}
478 and F_{Wood} will be the major fluxes to have influence on simulated E_{LUC} . To facilitate the demonstration of
479 model behaviour, we refer to F_{Inst} and F_{Wood} collectively to as “LUC-associated direct fluxes” and their
480 variations will be examined in detail by using an idealized grid cell simulation.

481

482 The model developments presented here enable us to make two parallel simulations that include LUC:
483 with and without sub-grid age dynamics. Their simulated E_{LUC} can thus be compared, to separate the
484 effect of including sub-grid age dynamics. Henceforth for brevity, we denote the simulation without
485 sub-grid age dynamics as $S_{ageless}$, and the one with age dynamics as S_{age} .

486 2.2.2 Idealized simulation on a single grid cell

487 We conducted an idealized grid cell simulation with prescribed land cover and LUC matrices, to compare
488 in detail the simulated carbon pools and fluxes between S_{age} and $S_{ageless}$. The geographical coordinates of
489 the simulation site are 9.25°S, 18.25°E at a 0.5° global grid, in the north of Angola, Africa, where the
490 miombo woodlands are known to be subject to practices of shifting cultivation. The ESA CCI land cover
491 map for the 5-year period of 2003–2007 (<https://www.esa-landcover-cci.org/>) shows a dominant fraction
492 of tropical deciduous broadleaf forest for this grid cell. Hence for the idealized experiment, the initial
493 vegetation composition is prescribed as 85% of tropical deciduous broadleaf forests and 15% of C4
494 croplands. As we will focus on the LUC impacts, other model forcings (climate, atmospheric CO₂, etc.)
495 are held constant, with climate input data recycling the year of 1901 (CRUNCEP-v5.3.2 climate data,
496 <https://esgf.extra.cea.fr/thredds/fileServer/store/p529viov/cruncep/readme.html>) and atmospheric CO₂
497 concentration being fixed at 350 ppm. The model is tested for a hypothetical scenario of constant annual
498 land turnover with 5% of grid cell area between forest and C4 cropland. Forest harvest of the same annual
499 areal fraction is expected to have largely similar impact. The spin-up was run for 450 years until biomass
500 and soil C stocks reached equilibrium and the mean annual net biome production (NBP) was close to zero
501 without including any LUC. Starting from the spin-up, a transient simulation with the prescribed LUC
502 matrix was performed for 100 years.

503 2.2.3 Simulation over Southern Africa

504 Subsequently, the model behaviour has been documented for a real-world case over the region of
505 Southern Africa (south to the equator of the African continent). All three LUC types occurred historically
506 in this region, making it ideal to demonstrate model behaviour regarding forest cohort dynamics as
507 presented in Fig. 5. This regional simulation serves a single purpose — to further exemplify model
508 features that cannot be sufficiently demonstrated over a grid cell.

509
510 The regional simulation is done at 2° resolution for 1501–2005. We used the land use reconstruction from
511 LUH1 covering 1501–2013 (Hurt et al., 2011, http://luh.umd.edu/data.shtml#LUH1_Data) re-gridded
512 from the original 0.5° to a 2° spatial resolution. We derived from the LUH1 dataset the matrices of the
513 three types of land use change: net land use change, land turnover and wood harvest. Land turnover
514 information is extracted from LUH1 as the minimum land fluxes between two vegetation types. **Wood**

515 **harvest from primary and secondary forests in LUH1 is used, while wood harvest from non-forest**
516 **is not.** Climate forcing data are from CRUNCEP-v5.3.2 at a 2° resolution. For the spin-up, climate data
517 were cycled from 1901 to 1910, with atmospheric CO₂ concentration fixed at 1750 level (277 ppm). In
518 the transient simulation, atmospheric CO₂ concentration began to increase in 1750, climate data were
519 varied starting 1901. The dynamic vegetation module was turned off, in order to apply the prescribed
520 historical land use change. Factorial simulations are conducted to highlight changes in areas of different
521 forest cohorts when different LUC processes are included, as shown in Table 4.

522

523 Each forest MTC has six CFTs to represent six cohorts. The woody mass thresholds are set in a way that
524 they correspond roughly to the woody masses at ages of 3, 9, 15, 30, 50 years, and the mature or primary
525 forest **(with an age greater than 50 years)** during the spin-up simulation, respectively, for Cohort₁ to
526 Cohort₆. The Cohort₃ with an age of 15 years is the primary target for secondary forest harvest and land
527 turnover (or shifting cultivation), corresponding to the mean residence time of 15 years of shifting
528 cultivation assumed in LUH1 data (Hurtt et al., 2011). We set two CFTs for each herbaceous MTC with a
529 high and low soil carbon density, respectively. The CFT thresholds of soil carbon stock are the same for
530 all herbaceous MTCs. We first calculate the maximum soil carbon stock of all MTCs (including the forest
531 ones) at the end of spin-up for each grid cell, and cohort thresholds are then taken as this maximum value
532 and its 65% value. Because the energy balance in ORCHIDEE-MICT is resolved for the average of all
533 CFTs over a grid cell, and the hydrological balance is resolved for three sub-grid water columns (i.e. the
534 water column of bare soil, forest and herbaceous vegetation), we expect the factors influencing soil
535 carbon decomposition (e.g., soil temperature, soil moisture) to have little variation among CFTs of the
536 same MTC. This justifies the small number of herbaceous CFTs, for the sake of computation efficiency.

537 **Overall, this feature of separating herbaceous MTCs into multiple cohorts is coded more as a**
538 **“place holder” for the current stage of model development rather than having solid scientific**
539 **significance. Fully tracking soil carbon stocks of different vegetation types and their transient**
540 **changes following land use change, would require a much larger number of cohorts than used in**
541 **this study.**

542 **3 Results**

543 **3.1 Grid cell simulations with and without sub-grid forest age dynamics**

544 **3.1.1 Temporal patterns of biomass carbon stock during the spin-up and transient simulations**

545 Figure 6a and 6b exhibit the evolution of above- and belowground biomass for both S_{ageless} and S_{age}
546 simulations, for the spin-up and transient simulation for a test grid cell located in Angola. **The results for**
547 **the S_{age} simulation are shown for individual cohorts (Cohort₁ to Cohort₆).** For this test an annual

548 forest-cropland turnover of 5% of the grid cell area was imposed. Figures 6c-h present changes in the
549 ground fractional cover of different forest cohorts during the transient simulation. S_{ageless} and S_{age} share the
550 same biomass accretion with time during the spin-up, but S_{age} shows a succession of forest cohorts —
551 with biomass moving from one cohort to the next (Fig. 6a & 6b). At the end of the spin-up, all biomass is
552 found in Cohort₆ (i.e., the oldest cohort), with an initial forest cover of 85%.

553
554 More differences emerge when entering the transient simulation. Aboveground biomass in S_{ageless} shows
555 an initial sharp drop followed by a more gradual decline under constant land turnover, because biomass of
556 the single forest patch is constantly ‘diluted’ by merging with the new forest patch with a low biomass,
557 which is established as a result of land turnover (see also Fig. 1). Belowground biomass, however, shows
558 a corresponding initial drop but then slightly increases. Eventually, both above- and belowground
559 biomass stocks in S_{ageless} reach a new equilibrium, which are lower than their values at the end of the spin-
560 up. By contrast, in S_{age} , the fraction of Cohort₆ declines with the start of the transient simulation because
561 of conversion to cropland. This decline continues until the 12th year, after which the remaining Cohort₆
562 covers only 30% of the grid cell (Fig. 6h). Younger cohorts are progressively created as forests restore
563 after shifting agriculture abandonment, with the Cohort₁ (i.e., the youngest one) appearing during the
564 initial 6 years after the start of LUC, after which its biomass is moved into Cohort₂ (Fig. 6c & 6d).
565 Cohort₃ starts to appear at the 12th year when biomass in Cohort₂ moves into it. Then its coverage declines
566 as this cohort, rather than Cohort₆, is used as the source for shifting cropland, according to the model rule
567 that secondary forest is taken prior to primary forest in the land turnover (Fig. 5). After the initial 15 years
568 (the rough age of Cohort₃), the fractions of Cohort₁, Cohort₂ and Cohort₃ reach a dynamic stable state. **As**
569 **Cohort₃ is being constantly converted to cropland, it has never developed into Cohort₄ or Cohort₅.**
570 **This explains the zero fractions of these two latter cohorts in Fig. 6f & 6g.**

571
572 While the aboveground biomass continuously grows during the spin-up, the belowground biomass first
573 increases with time and then slightly declines before reaching the equilibrium value. This is because
574 ORCHIDEE-MICT has a preferential allocation of NPP to belowground sapwood when forests are
575 young. The small decline in belowground biomass in the late spin-up stage thus results from an almost
576 stabilized NPP (under a big-leaf approximation), a reduced belowground allocation and a constant
577 mortality. Because of this feature, ORCHIDEE-MICT creates a higher belowground biomass in younger
578 forest cohorts (e.g., Cohort₂ and Cohort₃ in Fig. 6a & 6b) in S_{age} than the single forest patch in S_{ageless} in
579 the transient simulation. However, the aboveground biomass in younger Cohort₂ and Cohort₃ in S_{age} is
580 lower than S_{ageless} . The difference in biomass influences the simulated E_{LUC} between these two
581 simulations, as we will discuss in detail later.

582 3.1.2 LUC-associated direct carbon fluxes

583 As shown in Fig. 7a, in S_{ageless} , the instantaneous carbon flux resulting from LUC follows the same
584 temporal pattern than the aboveground biomass, as it is simulated as a fixed fraction of aboveground
585 woody mass (sapwood and heartwood) (see Sect. 2.1.5). In S_{age} , for the initial 12 years, the Cohort₆
586 (undisturbed mature forest) is cleared, so that the instantaneous LUC carbon flux is higher than that in
587 S_{ageless} (where the biomass of the single forest patch is reduced immediately when the land turnover
588 starts). After that, the instantaneous flux shows a stark drop in S_{age} when the Cohort₃ enters the land
589 turnover. Since then until the end of the simulation, S_{age} has kept a constantly lower instantaneous flux
590 than S_{ageless} because the LUC-perturbed equilibrium biomass is higher in the latter case (Fig. 6a). As a
591 fixed 10% of aboveground woody biomass enters the wood product pool with a 10-year turnover time,
592 delayed carbon emissions from wood products degradation in both simulations are smaller than the
593 instantaneous LUC carbon fluxes. They peak around the 12th year after LUC and remain stable afterwards
594 (Fig. 7a). Overall, S_{age} has a higher LUC-associated direct carbon flux than S_{ageless} for the first 12 years,
595 and a lower one afterwards (Fig. 7a). The cross point for the cumulative LUC-associated direct fluxes
596 equal in S_{age} and S_{ageless} is around the 20th year (Fig. 7b). When summing over the whole simulation period
597 (100 years), the cumulative fluxes by S_{ageless} is lower in S_{age} by about 11 kg C m⁻², or ~110 g C m⁻² yr⁻¹
598 (Fig. 7b) than S_{ageless} .

599 3.1.3 LUC emission and its disaggregation into underlying component carbon fluxes

600 As defined in Eq (4), the net LUC carbon emission (E_{LUC}) is diagnosed as the difference in NBP between
601 the LUC simulation and the control one. Since NBP is further a composite flux determined by carbon
602 uptake and releases (Eq. 3), the difference in $E_{\text{LUC}_{\text{age}}}$ and $E_{\text{LUC}_{\text{ageless}}}$ can be disaggregated into the effect of
603 each underlying flux, which differs between the LUC simulation and the control simulation. Figure 8
604 presents such disaggregation. All positive values indicate an enhanced carbon uptake or diminished
605 release in the LUC simulation compared to the control one, whereas negative values indicate the reverse
606 cases (i.e., negative values indicate a contribution to enhance E_{LUC}).

607

608 First of all, S_{ageless} (no age dynamics) simulates a larger magnitude (i.e., a larger absolute E_{LUC} value) of
609 mean annual E_{LUC} than S_{age} (with age dynamics), by about 26 g C m⁻² yr⁻¹. Second, for both simulations,
610 the simulated E_{LUC} is an outcome of LUC-associated direct fluxes being compensated for by changes in
611 other fluxes, all of which have an effect to reduce E_{LUC} in this example: NPP, heterotrophic respiration,
612 fire carbon emissions and agricultural harvest.

613

614 NPP is higher in LUC simulations than in the control. This is because young forests are established in the
615 former case (either by merging with existing forest patch or not), leading to a younger leaf age than in the

616 control simulation, which is parameterized to have a higher photosynthetic capacity than older leaves in
617 the model. This suggests the model can somewhat integrate the effect of recovering young forests or
618 intermediate-aged forests with a higher productivity than the old-growth forests, as reported by Tang et al.
619 (2014) using observation data.

620

621 Averaged over the LUC simulation period of 100 years, both S_{age} and S_{ageless} show lower heterotrophic
622 respiration (F_{HR}) than the control. This is because the biomass stock is lower in the LUC simulations
623 (despite a higher NPP, biomass turnover is accelerated due to site perturbation and wood collection in the
624 process of clearing forest for cropland), causing less litter input and less soil carbon stocks (data not
625 shown). The S_{age} simulation shows a much smaller reduction in F_{HR} , mainly because a higher
626 belowground litter is maintained, which results from a high belowground litter input out of land turnover,
627 driven by a high belowground biomass, as explained in Sect. 3.1.1 (Fig. 6a).

628

629 Decreases in fire carbon emissions (F_{Fire} , from prognostically simulated ‘natural fires’ but not ‘land-
630 clearing fires’) in the LUC simulations in contrast with the control are because the aboveground litter
631 (dominant fuel for fires) is reduced by land turnover. Reductions in fire emissions, and reductions in
632 heterotrophic respiration, are thus driven by the same process, i.e., a reduction in aboveground standing
633 biomass. LUC simulations also result in lower agriculture harvest (F_{AH} , from cropland) although there is
634 no change in the cropland area; this is due to lower biomass in young crop, as the crop harvest is assumed
635 as a constant fraction of the biomass turnover (i.e., routine mortality) at a daily time step. The lower crop
636 biomass in the LUC simulations here is because crop saplings are established on the first day of each
637 calendar year, right before the seasonal biomass peak for the southern hemisphere, which artificially
638 reduces the standing biomass.

639

640 Overall, the lower E_{LUC} magnitude in S_{age} is a result of the lower LUC-associated direct fluxes having
641 been partly compensated for by a higher heterotrophic respiration. The relative magnitudes between E_{LUC}
642 $_{\text{age}}$ and $E_{\text{LUC}}_{\text{ageless}}$ are dominated by these two fluxes, while other fluxes play a less important role.

643 **3.2 Forest cohort area changes as a result of historical land use change over Southern Africa**

644 One of the useful features of our model development is to account for sub-grid forest age dynamics as a
645 result of historical land use change, as illustrated in Fig. 9 for Southern Africa. When no land use change
646 is included (S_0 , the control simulation shown in light blue), the areas of all forest cohorts are constant
647 over time. Except that younger cohorts have a very small area ($<0.1 \text{ Mkm}^2$) (Cohort_2 and Cohort_3 ,
648 probably due to improper cohort thresholds on a very small number of grid cells), almost all forests are
649 found in Cohort_6 , which resembles mature forests. In S_1 where only net land use change is considered, the

650 area of Cohort₆ decreases consistently over time due to conversion of forest to other land cover types (Fig.
651 9a). Occasional increases in areas of other younger cohorts are also present, corresponding to the periods
652 when forest gain happens due to net land use change, for instance, afforestation or reforestation around
653 1700s and in the latter half of the 20th century (Fig. 9a). This is consistent with our rule that forest from
654 abandonment of agriculture is established in the youngest cohort (Fig. 5b – on the right), and progressive
655 movement of forests from younger to older cohorts are also visible as the small waves in the curves of
656 Fig. 9b–f.

657

658 In the S2 simulation with both net land use change and land turnover, large areas of younger forests, in
659 particular of Cohort₁ and Cohort₂, begin to appear as a result of continual creation of forests from land
660 turnover, and subsequent moving of forests from Cohort₁ to Cohort₂. Their temporal changes over time
661 follow those of the forest area subject to land turnover, as shown in Fig. 9a (green dashed line). The area
662 of Cohort₃, however, does not see as much increase as in the two younger cohorts, because forests of
663 Cohort₃ are the primary target for clearance in land turnover and thus are incessantly converted back to
664 (shifting) agriculture. As a result, about half of mature forests (Cohort₆) are left intact from LUC by 2005
665 (Fig. 9h). Most interestingly, when there is a decline in the turnover-impacted area around 1700s (the
666 green arrow in Fig. 9a), a corresponding decline in the area of Cohort₁ is found because these forests
667 move into the next cohort. This pattern of decrease in the current cohort accompanied by the according
668 increase in the next one then propagates into other older cohorts with time, which results in a delayed
669 increase in Cohort₅ around 1750s (Fig. 9g), and finally in Cohort₆ as well (but less prominent because of
670 its already large area). This demonstrates the model feature of older forest recovery in case of decreased
671 land turnover or wood harvest, as explained in Fig. 5b (right hand side). Last, when we further include
672 forest harvest in S3 simulation, because wood harvest area only started to rise in the middle of 20th
673 century, larger areas of Cohort₁ and Cohort₂ cohorts are found compared with S2 in the latter half of the
674 last century, and forest area in Cohort₆ is accordingly lower, being converted to younger cohorts as a
675 result of harvest.

676 4 Discussion

677 DGVMs, either used in an off-line mode or coupled with climate models, are powerful tools to investigate
678 the role of past and future land use change in the global carbon cycle perturbed by human activities
679 (Arneeth et al., 2017; Le Quéré et al., 2016). Therefore, a more realistic representation of LUC processes
680 in these models is a scientific priority. We included two new features in ORCHIDEE-MICT v8.4.2: gross
681 land use change and forest wood harvest, and sub-grid vegetation cohorts. In a recent review (Prestele et
682 al., 2016), proper representation of gross land use change or sub-grid bi-directional land turnover has been

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Supprimé: 3.2.2 Cumulative LUC
emissions .

... [1]

686 identified as one of the three major challenges in implementing LUC in DGVMs for credible climate
687 assessments, despite that these have already been pioneered by some models (Table 1). **Large**
688 **underestimation of LUC emissions would occur when gross land use change is ignored, as is shown**
689 **by several model results being reviewed in Arneth et al. (2017).**

690

691 Shifting cultivation, or forest wood harvest, or more in general forest management, often involves a stable
692 fallow length or rotation cycle, which involves secondary forests rather than primary ones. In tropical
693 regions, fallow lengths in shifting cultivation range from 10 to 40 years (Bruun et al., 2006; Mertz et al.,
694 2008; Thrupp et al., 1997; van Vliet et al., 2012), with a tendency of reduction in fallow length. In Latin
695 American tropics, agricultural abandonment have already led to prominent growth of secondary forests
696 (Chazdon et al., 2016; Poorter et al., 2016). Forest management, including wood harvest, is more
697 common in temperate and boreal regions. In European forests, rotation lengths depend on tree species,
698 regional climate and management purposes, ranging from 8–20 years in coppicing systems in southern
699 Europe to 80–120 years in northern countries (McGrath et al., 2015). The prevalence of secondary forests
700 associated with land use and land use change therefore calls for their representation in DGVMs,
701 especially when modeling land use change.

702

703 **To our knowledge, Shevliakova et al. (2009) has been the first study to include both sub-grid**
704 **secondary lands and gross transitions in the LM3V model, but the number of PFTs and secondary**
705 **land tiles are limited in their study (up to in total 12 secondary land tiles compared with 50 in our**
706 **study). Stocker et al. (2014) included secondary land in LPX-Bern 1.0 but only one tile of secondary**
707 **land is available. Yang et al. (2010) examined the contribution of secondary forests to terrestrial**
708 **carbon uptake using the ISAM model by explicitly including secondary forest PFTs, but they did**
709 **not include the dynamic clearing of secondary forests in land use change, nor shifting cultivation.**
710 **Therefore, none of these studies have included a dynamic decision rule regarding the ages of**
711 **cohorts to be targeted in different LUC processes or the possibility to target different cohort ages in**
712 **different geographical regions.** ORCHIDEE-CAN is especially designed to address forest management
713 and species change. Although certain land use change such as wood harvest and net land cover changes
714 are included, a more comprehensive LUC scheme addressing gross change is missing (Naudts et al.,
715 2015).

716

717 The gross land use change combined with sub-grid cohorts presented here has shown some promising
718 results. We first confirmed that including gross land use change leads to additional carbon emissions.
719 However, these additional emissions tend to be overestimated when secondary forests are not explicitly

720 accounted for. The idealized grid cell simulation well explained the mechanism driving such
721 overestimation in S_{ageless} simulations. The results presented here are closely linked with our model
722 parameterization and in particular, the decision rules regarding which forest cohorts to apply for specific
723 LUC processes (Table 2). Land turnover and secondary forest harvest are parameterized to target
724 intermediate-aged cohorts as a priority. This is the core mechanism driving the lower LUC emissions
725 when sub-grid forest age structure is accounted for.

726
727 As a preliminary effort to demonstrate the model behaviour, the land turnover parameterization is heavily
728 tied with the input LUC forcing data (LUH1), so that the age of Cohort₃ (as the primary target for land
729 turnover) is set as ~15 years, following the assumed mean residence time of shifting cultivation in LUH1
730 data set (Hurtt et al., 2011). The model simulations showed that this parameterization is crucial, because it
731 largely determines the rotation length in the model, and consequently, the amount of carbon stocks
732 subjected to LUC and the difference in estimated LUC emissions between the two model configurations
733 (S_{age} and S_{ageless}). **In this regard it should be noted that the information on rotational lengths of
734 shifting cultivation or forest harvest is spatially unbalanced and that at present no systematic global
735 compilation exists. The universal setting used in this study is due to the absence of such a
736 compilation. In fact, because the thresholds in woody mass to distinguish forest cohorts could be
737 configured via a spatial map in the model and such maps could vary among different years, and
738 because the primary cohort target is not hard-coded and can be parameterized as well, it is rather
739 straightforward to apply temporally and spatially different rotation lengths in the model.** Such a
740 feature is well considered in the model development design and could be tested when information on
741 spatially and temporally explicit forest rotation lengths or associated biomass thresholds is available.

742
743 In the following paragraphs we will discuss the decisions that were marked as “deliberate” and their
744 potential impacts on modeled LUC stocks and fluxes. First, the LUC module developed is intended for
745 usage within DGVMs, and forced with external data sets that provide information on land flows between
746 different land cover types. It is not intended to supersede a land use change model per se, which simulates
747 land use change using other available social and economic information such as population, food demand,
748 wood demand, etc. (Hurtt et al., 2011). In this sense, the LUC module implementation has to inevitably
749 take into account the details of information in forcing data that are available, and to reconcile the potential
750 mismatch between the model and forcing data. For example, the LUC module presented here can
751 accommodate forest wood harvest from primary and secondary forests when these two sources are
752 distinguished in the forcing data, but hierarchical decision rules are also made when the model and

753 forcing data disagrees (e.g., Fig. 5), such as that prescribed “secondary forest wood harvest” can actually
754 harvest a “primary forest” in the model if all younger cohorts are exhausted.

755

756 Second, because of this clearly defined border of the LUC module to use land areas as the input
757 information, model output from ORCHIDEE-MICT can potentially disagree with the socio-economic
758 information used to generate the LUC forcing data. For instance, crop yield simulated by ORCHIDEE
759 may differ with that used to convert food demand/consumption to cropland area, so that simulated crop
760 output or food production may disagree with historical food demand in the real world. The same applies
761 on forestry wood production: simulated harvest wood volume might disagree with the wood volume
762 actually used to generate the harvest area information — the harvested wood biomass information is
763 provided in LUH1 data set but not used as an input in the current stage of model development. This
764 largely raises the issue that, to what extent the information that drives land use change decisions can be
765 *internally* integrated into DGVMs, for example, to use directly crop production, rather than cropland area,
766 or wood volume, rather than forest harvest area as the model input. One potential obstacle is that
767 statistical information (e.g., on wood volume demand) is often available on regional basis (FAO global
768 forest resource assessment, <http://www.fao.org/forest-resources-assessment/en/>; eurostat,
769 <http://ec.europa.eu/eurostat/data/database>), and complex decision rules are needed to disintegrate such
770 information on spatial grids that DGVMs are operated on. But in general and over a long term, land use or
771 land management decisions need to be integrated directly into DGVMs. ORCHIDEE-CAN has integrated
772 forest management decisions based on simulated tree diameters and stand density, so that harvested wood
773 biomass is actually a model output that can be validated against historical statistical data (Naudts et al.,
774 2016).

775

776 The developments presented here mainly build on a model structure that distinguishes differently aged
777 cohorts. Nonetheless, we have built a better tool to address the impacts of historical land use change on
778 carbon cycle and climate with these developments. Forest demographics, which are shown to have great
779 impact on the current northern hemisphere carbon sink (Pan et al., 2011; Piao et al., 2009b), either as a
780 result of active afforestation, or agricultural abandonment or natural regeneration, could then be explicitly
781 investigated. **These developments also make it possible to verify modeled global and regional forest**
782 **age distribution using independent age information from either forest inventory or remote sensing.**
783 **The model version used here has incorporated the developments in pasture and cropland modules**
784 **(Chang et al., 2015; Wang et al., 2017). On a regional scale such as Europe, where the**
785 **comprehensive forcing data are available, it is possible to go beyond the carbon emissions only by**

786 | **LUC activities, but also to include LUC-induced changes in emissions of other greenhouse gases**
787 | **such as methane and nitrogen oxide.**

788 | **5 Conclusions**

789 | We have presented new developments made in a global vegetation model, to include gross land use
790 | change and forest wood harvest, in combination with explicit representation of sub-grid forest age
791 | dynamics. **Furthermore, a set of decision rules regarding the land cohorts to be targeted in different**
792 | **LUC processes have been implemented. The presented simulation results are specific of the**
793 | **ORCHIDEE-MICT model, but the methods are generic for other DGVMs. We demonstrated**
794 | **through an idealized pixel simulation that gross land use change leads to additional emissions but**
795 | **accounting for sub-grid land cohorts yields lower emissions than not. Over the region of Southern**
796 | **Africa, the model is able to account for changes in different forest cohort areas along with the**
797 | **temporal changes in different LUC processes, including regrowth of old forests when LUC area**
798 | **decreases.** Our developments provide the possibility to account for forest demography when evaluating
799 | LUC impacts on global carbon cycle and climate.

800 | **6 Code availability**

801 | The source code for ORCHIDEE-MICT version 8.4.2 is available online
802 | ([https://forge.ipsl.jussieu.fr/orchidee/browser/branches/ORCHIDEE-](https://forge.ipsl.jussieu.fr/orchidee/browser/branches/ORCHIDEE-MICT/tags/ORCHIDEE_MICT_GLUC_8.4.2)
803 | [MICT/tags/ORCHIDEE_MICT_GLUC_8.4.2](https://forge.ipsl.jussieu.fr/orchidee/browser/branches/ORCHIDEE-MICT/tags/ORCHIDEE_MICT_GLUC_8.4.2).) but its access is restricted to registered users. Requests
804 | can be sent to the corresponding author for a username and password for code access. ORCHIDEE-
805 | MICT is governed by the CeCILL license under French law and abiding by the rules of distribution of
806 | free software. One can use, modify and/or redistribute the software under the terms of the CeCILL license
807 | as circulated by CEA, CNRS and INRIA at the following URL: <http://www.cecill.info>.
808 |

809 | **7 Data availability**

810 | Primary data and scripts used in the analysis and other supplementary information that may be useful in
811 | reproducing the authors' work can be obtained by contacting the corresponding author.
812 |

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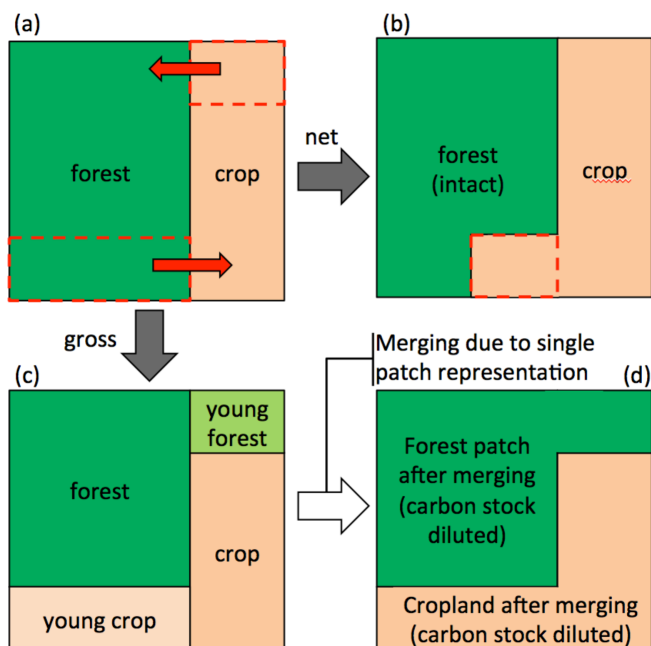
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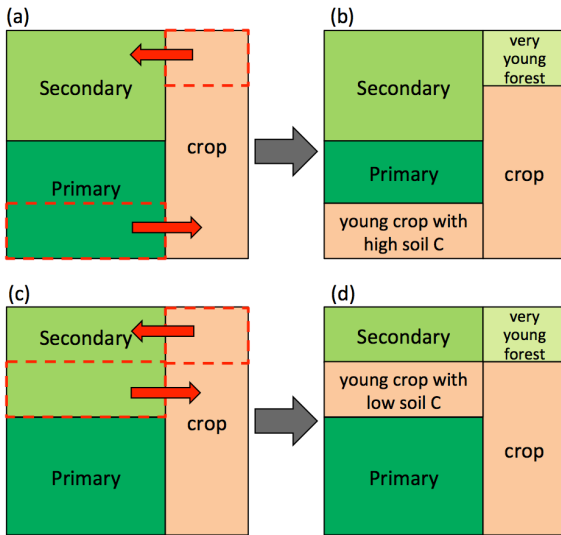
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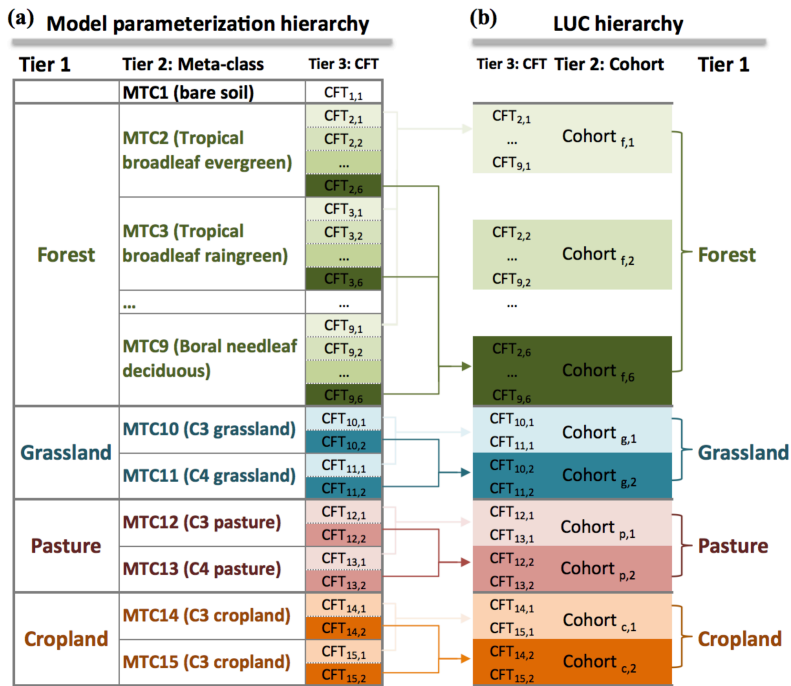
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Fig. 1 Schematic illustration of gross versus net land use change, with each land cover type being represented using a single patch within a model grid cell. The figure is adapted from Stocker et al. (2014). (a) Original fractions of forest and cropland before land use transitions. Dashed red rectangles indicate areas subject to LUC and red arrows indicate land flow direction. Here LUC consists of a net loss in forest and a simultaneous bi-directional flow between forest and cropland. (b) Post-LUC fractions of forest and cropland following the original LUC scheme of net transitions only in ORCHIDEE. Bi-directional land flow is omitted, with only cropland area being expanded to account for its net increase as a result of the net forest loss, as indicated by the dashed red rectangle. The soil carbon stock of the new cropland patch is an area-weighted mean between that of the original cropland, and the legacy stock from the former forest. Carbon stock of the remaining forest patch is left intact. (c) Intermediate post-LUC land cover pattern after accounting for gross transition. Both the net loss of forest and bi-directional land flows are accounted for, with two young patches of forest and cropland being established, respectively. (d) Final state of post-LUC land cover after accounting for gross LUC with no sub-grid cohorts. The carbon stocks of the remaining (original) forest and the newly created forest are immediately merged following LUC

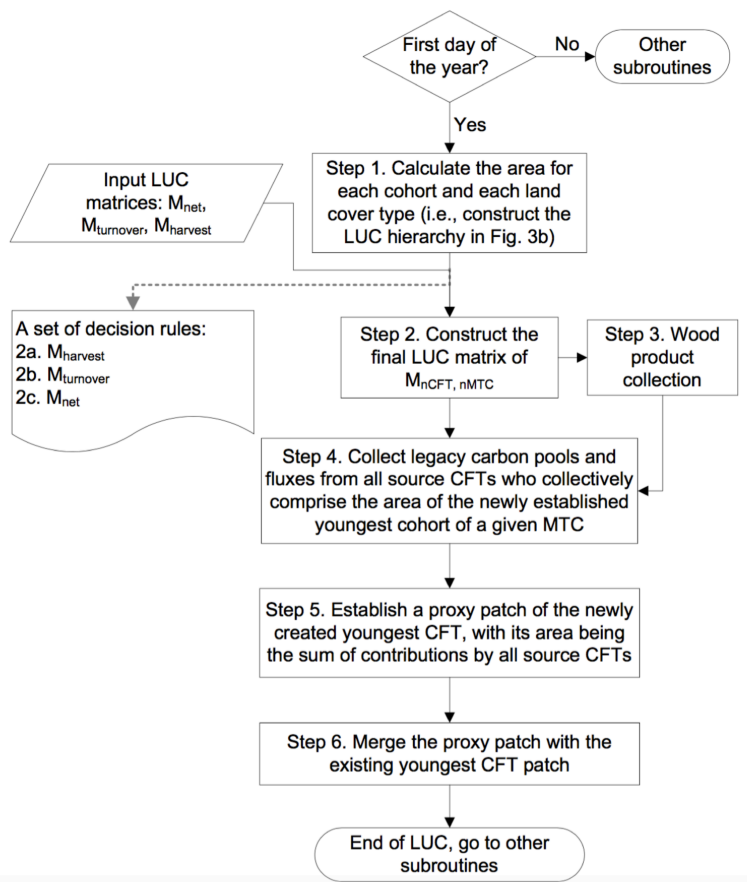
1035 because there are no sub-grid cohorts. The same applies for cropland as well. Note that although forest
1036 and cropland fractions are ultimately the same as in (b), the carbon densities are different.
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1041 Fig. 2 Gross land use change involving forests with different ages under a model scheme capable of
1042 representing sub-grid land cohorts. The figure is adapted from Stocker et al. (2014). LUC here is similar
1043 as in Fig. 1, except that forest is no longer a single ageless patch but consists of two patches of primary
1044 and secondary forests, i.e., having an age structure. (a) The same area of forest is converted to cropland as
1045 in Fig. 1a but conversion is made from primary forest. (b) Consequently, a ‘young’ cropland patch with
1046 rich legacy forest soil C is established. In the meanwhile, a very young forest patch is established due to
1047 the bi-directional gross land flux. Because the model uses multiple sub-grid patches to represent
1048 vegetation age structure (or differently aged cohorts), merging of patches with different carbon stocks is
1049 no longer necessary. Subplot (c) shows an alternative to (a) where conversion of forest to cropland is
1050 made on a secondary forest. Correspondingly, in subplot (d), which shows the post-LUC state of (c), the
1051 established young cropland patch will have lower legacy soil C than that in (b).
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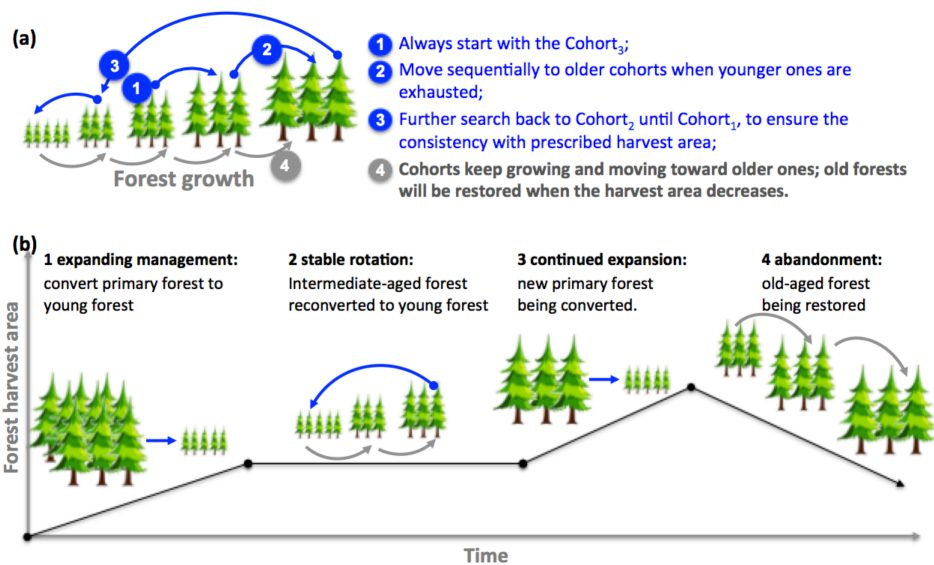
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 1054 Fig. 3 Two parallel hierarchies from the model parameterization and land use change perspective. (a)
 1055 Sub-grid cohort function types (CFTs) as inheritances of meta-classes (MTCs) and the corresponding
 1056 parameterization hierarchy. There are in total 14 vegetative MTCs corresponding to four vegetation types.
 1057 The notation of CFT_{ij} indicates that it inherits from MTC_i and belongs to the jth cohort (Cohort_i). Each
 1058 forest MTC has six cohorts, with Cohort₁ being the youngest and Cohort₆ the oldest, whereas each
 1059 herbaceous MTC is set tentatively to have two cohorts. Darker colors indicate older cohorts. (b) Within
 1060 the gross LUC module hierarchy, Tier 3 remains the level of CFT, but CFTs are re-organized to derive the
 1061 Tier 2 information based on the level of cohorts, under the same Tier 1 as in (a). A cohort bearing the
 1062 notation of Cohort_{v,i} indicates it belongs to vegetation type 'v' (where 'v' could be forest, natural
 1063 grassland, pasture and cropland) and meta-class 'i'. This re-organization of the hierarchy from the left to
 1064 the right side is to prepare for properly allocating prescribed LUC transitions first onto the cohort level,
 1065 then further to different CFTs within each cohort.



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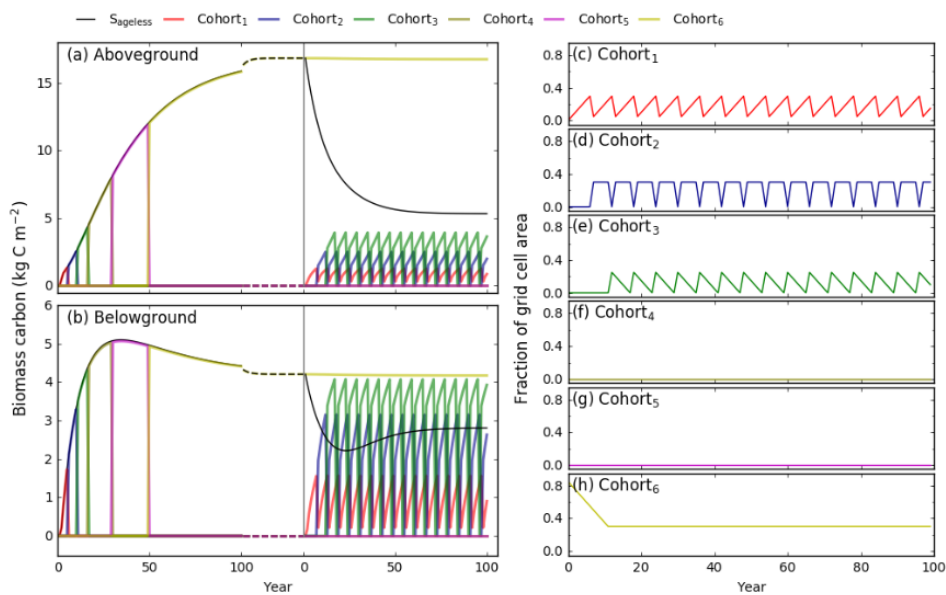
1067 Fig. 4 Schematic representation of the new LUC scheme in ORCHIDEE-MICT v8.4.2 accounting for net

1068 land use change, land turnover and forest harvest in combination with sub-grid cohort representation.

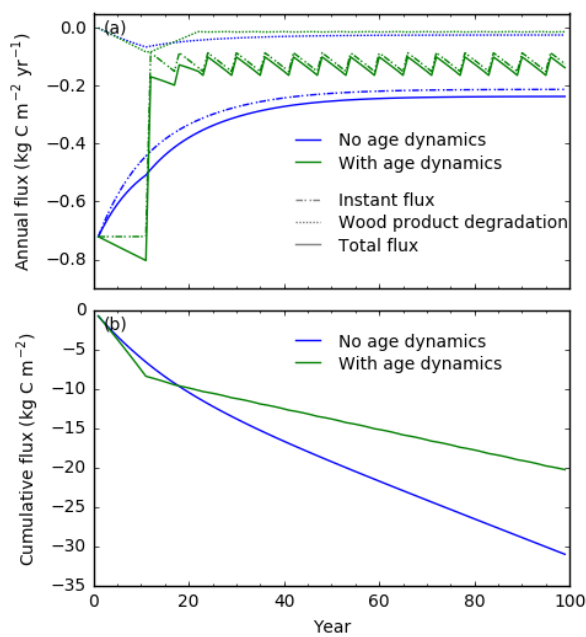


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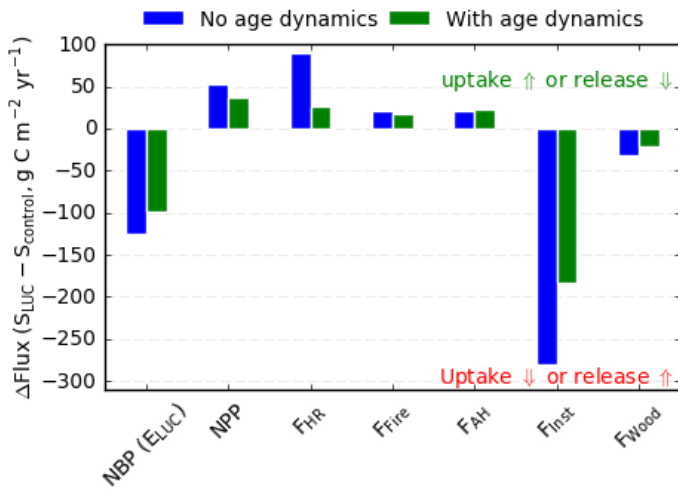
Fig. 5 Rules of selection of forest cohorts in secondary wood harvest to account for the dynamics in harvest area over time. (a) Rules of selection of forest cohorts (blue arrows). Clear-cut harvest (1) first starts with intermediate-aged cohort, then moves to older cohorts until the oldest one; (2) if the prescribed harvested area still cannot be satisfied, then the harvest will move back to the even younger cohorts (3) to the youngest one until the prescribed harvested area is fulfilled. Independent of the harvest activity is the movement of forests from younger cohorts to older ones because of growth (gray arrows). (b) Example of cohort dynamics along with temporal changes in the harvest area shown in the black curve: (1) before the onset of any harvest activity (i.e., after the model spin-up), only the oldest cohorts are available so harvest starts with the primary forest; (2) for a stable harvest area, a steady-state cycle is established involving only secondary forest (intermediate secondary cohorts being harvested is represented by the blue arrow, and younger growing cohorts are represented by gray arrows); (3) then with an increase in harvest area, more primary forests are harvested; (4) finally in this example, the harvest area decreases, and older cohorts are restored.



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 1085 Fig. 6 Biomass carbon stock as simulated by two model configurations without (S_{ageless}) and with sub-grid
 1086 age dynamics (S_{age} , comprising of Cohort₁ to Cohort₆) for (a) aboveground biomass and (b)
 1087 belowground biomass. Data shown are the biomass accumulation during the spin-up simulation (which
 1088 lasts for 450 years, from Year 0 until the end of dashed line) and transient simulation (which lasts for 100
 1089 years) where an annual forest-cropland turnover with 5% of the grid cell area is applied. **Forest clearing**
 1090 **for cropland primarily targets at the Cohort₃**. Vertical gray lines indicate the end of the spin-up and
 1091 the start of transient simulations. Subplot (c)–(h) show ground coverage by different forest cohorts as
 1092 fractions of grid cell during the transient simulation only.
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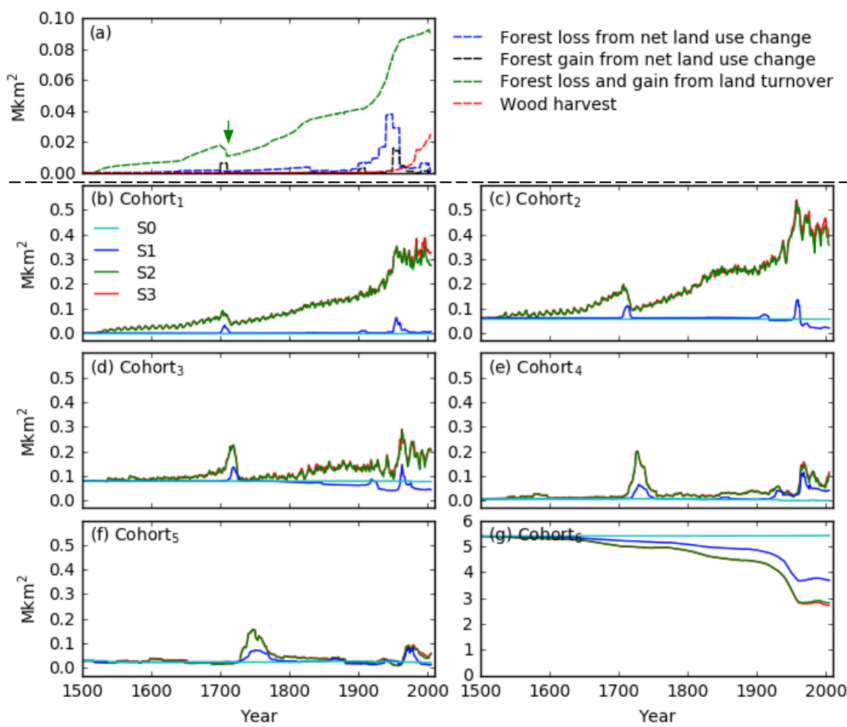
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 1095 Fig. 7 (a) Carbon fluxes directly associated with LUC (negative values for carbon lost from ecosystems):
 1096 instantaneous flux (dash-dotted line), flux from wood products degradation (dotted line) and the total flux
 1097 (solid line) for simulations with (green) and without (blue) sub-grid age dynamics. (b) Cumulative LUC-
 1098 associated direct fluxes (the sum of instantaneous and wood products degradation fluxes) for simulations
 1099 with (green) and without (blue) sub-grid age dynamics. Data are shown for an annual forest-cropland
 1100 turnover of 5% of the grid cell area for 100 years.
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1103 Fig. 8 Mean annual carbon flux differences between the LUC and control simulations over 100 years for
 1104 an annual forest-cropland turnover with 5% of the grid cell area for two model configurations: without
 1105 (blue) and with sub-grid age dynamics (green). Positive (negative) values indicate contributions to
 1106 enhanced carbon sink (source) in LUC simulation compared to the control one, either by stronger
 1107 (weaker) carbon uptake or smaller (stronger) carbon release. E_{LUC} is shown as a negative value here, i.e.,
 1108 the LUC simulation has a lower NBP than the control one, indicating an effect of net carbon source by
 1109 LUC.

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 1112 Fig. 9 Areas subject to historical land use change and the resulting modeled temporal changes in areas of
 1113 different forest cohorts in Southern Africa. (a) Areas subjected to historical land use change in which
 1114 forests are involved. Data are from LUH1 reconstruction (Hurtt et al., 2011) after adaption for
 1115 ORCHIDEE-MICT. Three types of LUC activities are shown and their effects elucidated by factorial
 1116 simulations (Table 4). These are: forest loss (blue dashed line) and gain (black dashed line) resulting from
 1117 net land use change, forest involved in land turnover (both loss and gain in equal amount, green dashed
 1118 line), and forest area subjected to wood harvest (red dashed line). (b)–(h) Areas of forest cohorts (Cohort₁
 1119 = the youngest, Cohort₆ = the oldest) for four factorial simulations (Table 4) where no land use change
 1120 occurs in S0, and the three LUC types are added in a factorial set-up in S1 (net land use change, blue solid
 1121 line), S2 (net land use change + land turnover, green solid line) and S3 (net land use change + land
 1122 turnover + wood harvest, red solid line). Note y-scale values in subplot (a) and (h) differ from others.
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Table 1. An overview of DGVMs having implemented gross land use change (shifting cultivation) and forest wood harvest.

Model name	Reference	Shifting cultivation	Wood harvest	Number of vegetation types	Number of secondary land tiles	Secondary vegetation types
LM3V	Shevliakova et al., 2009	Yes	Yes	Crop, pasture, primary and secondary vegetation	Up to in total 12 tiles	Dynamic secondary vegetation type according to the total biomass and prevailing climate
ISAM	Jain et al., 2013; Song et al., 2016	No	Yes	20 PFTs: 10 forests, 2 pastures, 2 grasses, 2 savanna, 1 shrubland, 1 tundra, 2 crops	1 tile for each secondary forest type	Tropical evergreen and deciduous forests, temperate evergreen and deciduous forests, and boreal forest
VISIT	Kato et al., 2013	Yes	Yes	14 PFTs: 8 forests/woodlands, 1 savanna, 1 grassland, 2 shrublands, 1 tundra and 1 cropland	1 tile for each secondary PFT	13 natural PFTs
JSBACH	Reick et al., 2013	Yes	Yes	12 PFTs: 4 forests, 2 shrubs, 2 grasslands, 2 pastures, and 2 croplands	No separate secondary lands	
LPX-Bern 1.0	Stocker et al., 2014	Yes	Yes	10 PFTs: 8 woody, 2 herbaceous	1 tile for each PFT	10 PFTs
LPJ-GUESS	Bayer et al., 2017	Yes	Yes*	9 natural woody PFTs, 2 natural grass PFTs; 3 cropland cohort functional types, 2 pasture PFTs	1 tile per newly created secondary land	Dynamic vegetation type according to prevailing climate and PFT competition
ORCHIDEE-MCT v8.4.2	This study	Yes	Yes	14 PFTs: 8 forests, 2 grasslands, 2 pastures and 2 croplands	Number of tiles parameterizable for each PFT	14 PFTs

* Wood harvest was not included in Bayer et al. (2017).

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1129 **Table 2 A set of implemented rules regarding cohort selection for different land use change**
 1130 **processes**

LUC process	Cohort decision rule
Primary forest harvest	Start with the oldest cohort, then move to younger ones
Secondary forest harvest	Start with an intermediate cohort (configurable), then move to older ones, and finally to younger ones.
Clearing of forest for net land use change	Start from the oldest cohort, then move to younger ones.
Clearing of forest for land turnover	Start with an intermediate cohort (configurable), then move to older ones, and finally to younger ones.
Conversion of herbaceous vegetation to forests or other vegetation	Start with the oldest cohort, then move to younger ones.

1131
 1132 Table 3. Fractions of aboveground woody biomass lost immediately to the atmosphere during a forest
 1133 clearing, and channeled to 10-year and 100-year turnover wood product pools. These fractions are
 1134 different depending on forest biomes.

	Tropical forest	Temperate forest	Boreal forest
F_{instant}	0.897	0.597	0.597
$F_{10\text{yr}}$	0.103	0.299	0.299
$F_{100\text{yr}}$	0	0.104	0.104

1135
 1136 Table 4 Factorial simulations to examine forest cohort dynamics when including different LUC processes:
 1137 net land use change, land turnover and wood harvest. The plus signs (“+”) indicate that the corresponding
 1138 processes (matrices) are included in the simulations. Only simulations with sub-grid age dynamics are
 1139 done, with $S0_{\text{age}}$ having no LUC activities to $S3_{\text{age}}$ including all LUC processes.

Simulations and LUC processes included

Simulations	Net land use change	Land turnover	Wood harvest
$S0_{\text{age}}$			
$S1_{\text{age}}$	+		
$S2_{\text{age}}$	+	+	
$S3_{\text{age}}$	+	+	+

1140