RESPONSE TO EDITOR

Editor: As explained in https://www.geoscientific-model-development.net/about/manuscript_types.html the preferred reference to the code used for the publication is through the use of a DOI which then can be cited in the paper. For projects in GitHub a DOI for a released code version can easily be created using Zenodo, see https://guides.github.com/activities/citable-code/ for details.

> We appreciate the request. We have archived a permanent version of the model code, in its entirety, to Zenodo <DOI: 10.5281/zenodo.4409331>.

RESPONSE TO REVIEWER #1

Reviewer_1_ Main_Comment_001: Disturbance history and disturbance regime are important drivers of terrestrial biosphere dynamics and ecosystem function, but they are rarely represented in dynamic global vegetation models. Here Calle and Poulter describe their age-class implementation in the LPJ model (LPJ-wsl v2.0), and present a series of simulations seeking to highlight the effects of disturbance history on vegetation structure and the carbon cycle, as well as the global patterns of ecosystem age when accounting for fire and land cover and land use disturbances. This work provides an important model development and can become an important contribution to the modelling community, once some issues, which I describe below, are addressed by the authors.

The current model description provides an overview of the age structure in LPJ-wsl and includes some examples on how this module works (Figures 1 and 2). However, some mechanisms are not sufficiently described and deserve attention, especially in a journal like GMD. For example, in section 2.2.1, I could not tell how each within ageclass element ($f_{i,j}$) is represented in the model: are they treated as "independent" components (i.e., available soil water and light computed independently for each within ageclass element), or do all the elements in the same age class share the resources?

> Agreed, this could be clearer. The hierarchical structure of the model is described on L120. All ageclasses share the same gridcell inputs (climate, co2, radiation). The state variables of plant available soil water and light can differ among ageclasses, which is mainly controlled by plant water demand and plant cover, respectively.
>
> The *within* ageclass elements are not independent and every *within* ageclass element has the same exact state variables, including the same soil water and light. The *within* ageclass elements are simply a vector representation of areas for each age-unit in the ageclass. As such, we only simulate processes at the ageclass level, and the *within* ageclass elements are a simple method for a 'smooth' transition between ageclasses (i.e., no big jumps in state variables when ageclasses transition). In theory, we can simulate processes independently for each within ageclass element, but this is not practical or necessary.

Also, how do the age-width transitions work in the case of unequal age classes, considering that the age class transitions occur once a year? Does that mean that young age classes have fewer elements, or are multiple elements allowed to transition to another age class at the annual time step? These are mostly points for clarification and should be straightforward to address in a revised version.

> Correct, ageclass transitions occur only once per year. In the unequal-bin setup, young ageclasses have fewer elements. Each *within* ageclass element represents the areal fraction of a single age-unit, for either setup (equal-bin and unequal-bin ageclasses). Every year, all elements increment, but each element can only increment its position once per year (rate of change is 1). Per re-

sponse above, the main benefit for using unequal-bin ageclasses is to independently simulate processes and track state variables separately.
We added the text below Section 2.2.1 "An age-based model of ecosystems – sub-grid-cell patch dynamics. (bold is for emphasis, here only).

... The age-class module has a fixed number of age-classes that can be represented in a grid cell, but all age-classes are not always represented. **Age-classes are classified into 12 age-classes (patches) in fixed age-width bins, defined as the *unequalbin* or the *10yr-equalbin* age-width setup (Table 1). Each ageclass contains *within* ageclass elements, which are simply a vector representation of areas for each age-unit in the ageclass. The *within* ageclass elements are not independent and every *within* ageclass element has the same state variables, including the same soil water and light. As such, we only simulate processes at the ageclass level, and the *within* ageclass elements are a simple method for a 'smooth' transition between ageclass. In theory, we can simulate processes independently for each within ageclass element, but this is not practical or necessary. The main benefit for using equal-bin or unequal-bin ageclasses is to independently simulate processes.** The age-widths of the age-classes in the *10yr-equalbin* setup correspond to common age-widths of classes used in forest inventories. The *10yr-equal*bin age setup is used for all global simulations, whereas the *unequalbin* setup is applied to explore model dynamics at the level of a single grid-cell; simulation details in next section.

The authors compare the effect of some model settings (e.g., enabling vs. disabling the age structure module), but no benchmarking is provided other than the comparison of the predicted forest structures with FIA plots. Consequently, several processes were not truly evaluated against observations or at least reported values in the literature. For example, when the authors compare the simulations with and without age-class dynamics (Figures 5, 6 and text referring to them), it is implied that the age-structure simulations are more reasonable, but the authors do not provide any reference to observations. Although the simulations are idealized, some values from literature could at least indicate whether the time scale for recovery is at least in the right order of magnitude at different biomes.

There is value in improving modeled forest structure. The comparisons to FIA plot data are intended to provide confidence in the model's capacity to reproduce forest structural properties – a form of benchmarking. We provide a new comparison of the age distribution by continent simulated by LPJ-wsl v2.0 and compared to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data (SM Figure 11). The comparison shows that the simulated ages are consistently older than the GFAD dataset.

This work is not intended to be a benchmarking/optimization paper, although we intend to do this in the future. Benchmarking, optimizing model parameters, identifying and improving model processes is no small task. Throughout the Discussion sections we use phrasing throughout that accounts for our uncertainty in our simulation results. We make this clear in the first section of the Discussion and we add comments to clarify our uncertain position, as below.

"(4.1) Distribution of Ecosystem Age on Earth
... Our model developments are not optimized to match observations, although we are working toward this end. Future goals are to assimilate stand-age related data, such as remotely-sense canopy data and stand index growth curves, to align model processes with observations. ..."

"(4.2 Age Dynamics Increase Turnover) ... That turnover increases when explicitly simulating ageclasses is a natural expectation, but the magnitude of the simulated turnover between carbon pools is less certain until detailed benchmarking is conducted. ..."

Finally, the fire disturbance is presented as the critical determinant of forest age distribution, but no assessment of the fire module is provided. I understand and agree with the authors that fire datasets such as GFED will include fire types currently not represented in LPJ-wsl and a comparison of carbon emissions is not possible due to the risk of double counting, but they could be still useful for verifying whether spatial distribution and the inter-annual variability of fire disturbance predicted by LPJ-wsl is reasonable or not.

> The fire module was left unchanged from prior versions. The Glob-FIRM fire module has been previously evaluated in great detail by Thonicke et al. 2001, and Hanston et al. 2016. There are better efforts at answering the utility or realistic representation of simulated fire dynamics than we can do justice in this paper. This was the major aim of the Fire Model Intercomparison Project (FireMIP). We make it clear that the fire module needs improvement, it underestimates burned area, and that the resultant effect is older ecosystem ages.
>
> In the second paragraph of the Discussion, we added clarifying remarks as below. (bold for emphasis, here only)
>
> "...Furthermore, the fire module has been well evaluated at global scale (Thonicke et al. 2001) but **it needs improvement because it is overly simplistic and underestimates global burned area** (Hantson et al. 2020), so it is more likely that effects of fire are much greater than simulated in this study. It is clear then that this study underestimates disturbances rather than overestimates them, and as such, these simulations overestimate ecosystem age. But again, additional disturbances would only lead to younger age-classes, enhancing the role of age dynamics in regional and global carbon cycles."

Specific Comments

Reviewer_1_Specific_Comment_001: L58. Re-write this sentence, so it is clear that some models do account for demographic effects, including a few that were cited in the previous sentence.

> The text was changed accordingly, as below, to clarify that some models already account for demographic effects.
>
> "Following a call to the science community to improve demographic representation in models (Fisher et al. 2015), there is now a growing list of global models that are capable of simulating global ecosystem demographics (Gitz and Ciais 2003, *Model*: OSCAR; Shevliakova et al. 2009, *Model*: LM3V; Haverd et al. 2014, *Model*: CABLE-POP; Lindeskog et al. 2013, *Model*: LPJ-GUESS; Yue et al. 2018, *Model*: ORCHIDEE MICT; Nabel et al. 2019, *Model*: JSBACH4), although more models need the capability to represent landscape heterogeneity in forest structure and function."
>
> Note that few models that simulate the global terrestrial surface account for demography. CABLE, LPJ-GUESS and now JSBACH are the few exceptions that now include sub-grid-cell heterogeneity in ecosystem demography. ED2 does have demographic capabilities, as do many other regional and landscape-scale simulation models, but such models have not been run globally. The lack of global simulations demographic models is primarily due to the computational burden of ageclass representation, which we overcome with our methodological approach.

Reviewer_1_Specific_Comment_002: L94. The authors mention permafrost and wetland methane but these features are not described anywhere. Considering that these are features in the new code, shouldn't they be described somewhere?

The LPJ-wsl v2.0 model is written as a fully modular program. Compiler flags are used to turn on/off modules. In this paper, we did not use the wetland methane or permafrost compiler flags.

Reviewer_1_Specific_Comment_003: L132. This is a good and clear explanation, but I wonder if the authors could also highlight the consequences of adding age-classes to the representation of the microenvironments in LPJ-wsl (light, water and perhaps nutrient availability). Also, was there any reason why natural disturbances (e.g., tree fall) cannot create new age classes?

The ageclass module doesn't model microenvironments per se, rather it is intended to represent landscape heterogeneity, but the remark is well taken and it is a good point. The ageclass or patch size is at minimum ~2.5 km2, with a maximum of ~50 km2 (0.5 degree grid cell). Resource availability (space, light, water, *no* nutrients) is implicitly modeled as a function of a mean-individual 'big-leaf' plant functional type (PFT), with each PFT having properties of stem density, fractional plant cover, tree height, and other attributes that govern water demand and space filling properties.

Other disturbances such as tree fall can create new age classes, yes. Our model only includes the disturbances of fire and land use and land management, but other disturbances can certainly be added. The main text has similar phrasing in the Discussion section 4.3 Opportunities for Improving Modelled Age-dynamics."

"..There a number of opportunities for refining the age-module. Incorporating additional disturbances within the model, which will help simulate age distributions more consistent with inventory (Pan et al. 2011a) and satellite (Pugh et 680 al. 2019b) data and contribute to more scientifically relevant questions. Modeled disturbances need not be complex to explore their effects on age distributions, they only need to reset a fractional area to the youngest age-class. ..."

Reviewer_1_Specific_Comment_004: L140–155. This is not entirely accurate. In some cohort-based models, a patch represents a collection of gaps with similar forest structure. In such models, fusing patches that have similar structure simply means that the structures of patch A and patch B are sufficiently similar so that the merged patch can represent all gaps in A and B (and thus representative of a larger area). At least for ED2, the patch fusion is not determined by one state variable as implied in the text, but by the vertical LAI profile (Fisher et al. 2018).

In ED2, the vertical LAI profile can still be considered a state variable of the patch, even if it is emergent from the underlying PFT cohorts. The point we make is three-fold, (1) some models do not have fixed patch size (LPJ-GUESS has a fixed patch size and patches do not merge); (2) models that have variable patch size require merging similar patches otherwise the patches could be created every year and computation will slow to a crawl. Merging is a computational solution to patch creation. (3) merging patches based on a limited set of state variables, or even a single state variable, is an arbitrary decision along a single axis of similarity between patches. We clarify as below in Section "2.2.1 An age-based model of ecosystems – sub-grid-cell patch dynamics":

"We also employ merge age-classes (patches), but we do not employ merging rules along arbitrary axes of similarity. We fix the number of age-classes *a priori*, similar to LPJ-GUESS in that there is a maximum number of age-classes. Instead of forced merging to reduce computational burden (as in ED2), a fraction of the age-class always transitions to an older state, and a fractional area can transition and merge with the next oldest age-class."

Reviewer_1_Specific_Comment_005: Section 2.2.2. I understand that the fire model has been previously described, but more detail would help here, as fires are critical for the results shown later in the paper. Instead of describing the model qualitatively, the authors could provide the basic equations and also a table with the PFT-specific fire resistances (SI text and table would be fine).

The fire module is described in greater detail in other papers (Thonicke et al. 2001, Sitch et al. 2003). Yes, the fire module is important for simulating disturbances, but we do not modify parameters in the fire module or alter the process representation in this paper. The GlobFIRM module requires much needed improvements or replacement with another fire module. The GlobFIRM module clearly underestimates burned area, both regionally and globally. The assessment of GlobFIRM, relative to other fire modules and datasets, are already reported elsewhere (Poulter et al. 2015, doi:10.1002/2013GB004655; Hantson et al. 2020, doi: 10.5194/gmd-13-3299-2020).

Reviewer_1_Specific_Comment_006: L219–221. Presumably the fractional area abandoned/logged goes entirely to the youngest element within the youngest age class (f0,0, following your notation in Eq. 4), is this correct?

Yes, correct.

Clarify. Also, does it mean that the model assumes that all recently disturbed areas have similar structure of survivors? This may be fine for abandoned and clear-cut logging, but not very appropriate for fires and selective logging.

The model does not assume the structure of survivor trees. The structure of the abandoned/logged/burned area that goes into the youngest element is determined by the underlying process. For example, if wood harvest is prescribed to an area, but the demand for harvest biomass is satisfied before all biomass is removed, then there will be 'survivor' trees on the youngest element stand. If a fire occurs on a stand, but the fire does not burn all the PFTs, then there will be survivor PFTs on the stand.

Reviewer_1_Specific_Comment_007: Section 3.1. Are there allometric equations that relates carbon stocks, vegetation height and stem number density in LPJ? I wonder if this could explain the consistently lower stem densities, and if the biomass distribution across size would look more/less similar to the plot data.

Yes, there are space filling 'packing' constraints on stem density, based on allometric rules for size/height of PFTs. Yes, it could help explain the lower densities in LPJ-wsl v2.0 relative to the FIA plot data. Moreover, LPJ-wsl v2.0 does not represent vertical complexity, such as understory growth, which would increase stem density.

Reviewer_1_Specific_Comment_008: Section 3.1.2. I may be missing something here, but I cannot see which ecological processes are affected by choosing equal or unequal age classes. It almost reads like the only difference between the two simulations is how results are reported, please clarify the mechanistic differences between the two approaches. Also, as a point for discussion, it would be nice if the authors provided some insight of which approach is recommended.

We clarified in Section "2.2.1 An age-based model of ecosystems – sub-grid-cell patch dynamics" as below

"‥ The within-ageclass elements are not independent and every within-ageclass element has the same state variables, including the same soil water and light. As such, we only simulate processes at the ageclass level, and the within-ageclass elements are a simple method for a 'smooth' transition between ageclass. In theory, we can simulate processes independently for each within-ageclass element, but this is not practical or necessary. The main benefit for using equal-bin or unequal-bin ageclasses is to independently simulate processes. ‥"

"‥ The use of equal or unequal age class setups is more than just for reporting purposes. Resources available to plants (space, light, soil water) differ between age-classes but not within age-classes, and we limit the model to represent a total of 12 ageclasses. Also, there exists a greater range of forest ages at global scales and the equal age-class setup allows us to independently model resource dynamics for more of the terrestrial surface. If we had chosen the unequal-bin setup for global simulations, we would be independently modeling processes only for the youngest age-classes and we would lose capacity to independently model processes at intermediate and older age-classes."

Reviewer_1_Specific_Comment_009: L436–440. These results are a bit expected because recently disturbed patches are more dynamic, so having finer bins for young age-classes makes sense to me. But it is also unclear is the effect of different binning strategies on the final results.

The line reference (L 436-440) was in regards to the emergent pattern in the decline in NEP with age of stand. It is generally expected that NEP declines with increasing age, yes. However, we did not expect to find such consistent patterns between NEP and stand age. We clarify as below,

"The binning strategy is likely not a determinant of this pattern between NEP and stand age, which is evident in Figure 3 for both age-class setups. In this regard, we care less about the binning strategy and more that the emergent pattern is reflective of simulated model dynamics. This emergent pattern could lend itself to observational constraints if similar emergent patterns can be derived from forest inventory data in the future."

Reviewer_1_Specific_Comment_010: Section 3.2.2. Is a recovery of NEP in 5–6 years more reasonable than 30 years? I don't see why, this needs some independent evidence from observations. Also, some clarification is needed to explain why Rh is consistently higher in the no-age simulation. Shouldn't the stand-scale mortality (and turnover) be the same in both cases, and the only difference be how mortality (and turnover) are applied?

Agreed, we state throughout that future work requires additional benchmarking or data assimilation to align model processes with observational patterns.

After a disturbance event, Rh is consistently higher in the no-age simulation, yes. We try to explain the mechanisms that results in this model artefact in the aforementioned Section 3.2.2. Note that mortality and turnover are left unchanged in the model; these processes are the same for all model setups (no-age, equal-bin and unequal-bin setup). The processes of mortality and turnover, among all other processes, act on the state variables themselves.

Reviewer_1_Specific_Comment_011: L518–519. I agree with the authors on the need of more targeted simulation experiments, but if some of the variables mentioned are available from the LPJ-wsl output, then the authors could check the results to see if some hypothesized mechanisms could be ruled out.

More simulations could help explain the fire-age zonal patterns, yes. Ideally, we first would want to make sure that the fire module aligns with burned area observations. We think such investigation is beyond the scope of the current work, and leave it simply as an open question for future investigation.

Reviewer_1_Specific_Comment_012: L647. This would account for only part of the uncertainty. Parameter and process uncertainty in most models can be quite large.

Correct. The statistical model would be emulating a model defined by a specific set of parameters and processes. In an ideal world, the statistical parameters for climate sensitivity and stand age would be constrained by uncertainty simulations, bounded to realistic parameter values.

Reviewer_1_Specific_Comment_013: L688–690. It may be worth mentioning that this size distribution may vary across regions (e.g., Espírito-Santo et al., 2014) and even within region depending on abiotic factors (e.g., Asner et al. 2013 which the authors already cite).

We agree with the recommendation and rephrased as below. (bold for emphasis, here only).

"The distribution of forest gaps also has a predictable power-law relationship with size of the gap (Asner et al. 2013), **which can be allowed to vary across and within regions (Asner et al. 2013, Espírito-Santo et al. 2014),** and this fact lends itself well for representing gaps within the framework of the current age-module."

Reviewer_1_Specific_Comment_014: L700. It makes sense to end the text with a paragraph about future developments, but the current one is vague. Which specific features could be implemented and which ones should be priority?

We agreed that we could do better to prioritize model improvements for the readers. The text in Section 4.3 has been updated accordingly. The beginning of the section now starts as below, with added text to support the suggestions.

"In order of priority for improvement of the age-module: 1) improve age-class growth rates to align with observations, 2) improve representation of disturbances, 3) improve representation of early- and late-successional plant species and add vertical structural complexity such as understory/overstory canopy. Below, we provide suggestions and examples from the literature as how these improvements might be accomplished. ..."

Minor comments

Reviewer_1_Minor_Comment_001: L23. Explicitly say which latitudinal band has the lower age.

Edited accordingly.

Reviewer_1_Minor_Comment_002: L24. Land use change and land management were. . .

Edited accordingly.

Reviewer_1_Minor_Comment_003: L25. Does −21 yr correspond to both temperate and tropical areas? Clarify.

Yes, the difference (-21 yr) corresponds to both temperate and tropical zonal bands. Edited accordingly.

Reviewer_1_Minor_Comment_004: L81. “is” instead of “was”?

Edited accordingly.

Reviewer_1_Minor_Comment_005: L98. This sentence could be dropped, considering that version control software has been around for a very long time.

We agree. Edited accordingly.

Reviewer_1_Minor_Comment_006: L125. I don’t see a strong reason to use both patch and age-class throughout the text. It makes sense to keep the explanation here but use a single term thereafter.

We agreed, we now think use of the term ‘patch’ causes unnecessary confusion. We replaced all instances of ‘patch’ with ‘age-class’ throughout.

Reviewer_1_Minor_Comment_007: Eq. 4. Isn’t the fw,n(t + 1) term a form of fusion? I guess this depends on how independent the different elements within age-class are.

Yes, this is fusion or ‘merging’. We added clarifying text to the Section 2.2.1 to explicitly say that we also merge patches, but we do not merge along axes of similarity.

“... We also merge age-classes, but we do not employ merging rules along arbitrary axes of similarity. We fix the number of age-classes *a priori*, similar to LPJ-GUESS in that there is a maximum number of age-classes. Instead of forced merging to reduce computational burden (as in ED2), a fraction of the age-class always transitions to an older state, and a fractional area can transition and merge with the next oldest age-class. ...”

Reviewer_1_Minor_Comment_008: L175–187. Is there any reason why some of the fractional areas are fw,n and others are Fw,n? If not, then use a single notation.

The text was changed to reflect single elements, fw,n

Reviewer_1_Minor_Comment_009: Also, in Eq. (5), is it correct to say that F 0 totalj (t) = Ftotalj (t) − fw,j (t)?

The meaning of the Reviewer’s comment is unclear.

We edited Eq #5 to show that the sum of fractional areas for all age classes and age widths equals F_total

Reviewer_1_Minor_Comment_010: L202. Rewrite this sentence. Conceptually yes, the approach does seem to avoid dilution, but no example from actual model simulations was provided. Also showing that this approach works in LPJ-wsl is different than saying that the age-class/agewidth approach solves the dilution issue. I am not even sure this is an issue with other models or the default LPJ, are there examples of this happening from the literature or in other LPJ simulations that the authors carried out?

There are no other examples showing this issue in the literature. We conduct a single-pixel idealized simulation to show this effect directly. In the Panel for Veg Carbon in Figure 5, the post-disturbance biomass in the no_age simulation is diluted. This is the extreme scenario for a single stand, which can be thought of as a simulation within only 1 age class.

When averaging two numbers, the mean will always be less than the maximum value, by definition. The average over a vector of carbon densities (C m^{-2}), which takes into account the contributing fractional areas, will give a mean carbon density that will always be lower than the maximum carbon density in the vector. Hence a dilution of the densities will always occur. The VTFT method tries to reduce this effect. Absent computational constraints, we could represent every land fraction separately and avoid dilution.

Reviewer_1_Minor_Comment_011: L223. “to” instead of “->”

Edited accordingly.

Reviewer_1_Minor_Comment_012: L233–235. This assumption seems counter-intuitive at least in the tropics, where young secondary forests have high deforestation rates (e.g., Nunes et al. 2020; Wang et al. 2020).

We agreed. We changed the text to read “This rule will always result in greater land-to-atmosphere fluxes than if rules were employed that allowed younger age-classes to be preferentially deforested.”

Reviewer_1_Minor_Comment_013: L235. At least for me, this seems the opposite of a conservative estimate.

Agreed, we corrected the text as above.

Reviewer_1_Minor_Comment_014: L262. “were” instead of “was”

Edited accordingly.

Reviewer_1_Minor_Comment_015: L275. Because readers may not be familiar with FIA plots, include the total plot area and the minimum DBH measured over the entire plot area. Also add the metric equivalents for all diameter references.

We edited and reword the text accordingly. For clarity, it now reads as below:

“... The FIA plot level data are composed of 4 circular sub-plot sample areas (168 m^2), wherein attributes of all trees with Diameter at Breast Height (DBH) ≥ 5.0 inches (12.7 cm) diameter are recorded. ...”

Reviewer_1_Minor_Comment_016: L293. Is the 5% based on any real mechanism?

No, it is a simple way of maintaining fractional areas in every age-class for every year of the simulation. If we did not prescribe disturbance (5% annual clearing), then might not have a distribution of age-classes within a grid-cell. Alternately, we might have a situation where young age-classes are only present once during the simulation, which could occur during dry or wet years.

Reviewer_1_Minor_Comment_017: L306. “Data” instead of “Date”

Edited accordingly.

Reviewer_1_Minor_Comment_018: L375. This seems a software-specific remark, mention and cite the software.

If the line reference above is correct (L 375), then the text refers to statistical modeling, which is not software-specific.

Reviewer_1_Minor_Comment_019: L434. Clarify this text. What is the field-based evidence, and whether the results are consistent with the evidence in a quantitative or qualitative manner (from reading the text it looks like it is the latter).

We edited the sentence as below for clarity. (bold is for emphasis)

"... The age-class module **qualitatively** demonstrates NEP-age relationships..."

Reviewer_1_Minor_Comment_020: L477. What are the differences in GPP?

Within the paper, we focus on differences in NPP as opposed to GPP, which is less certain. NPP is much more easily constrained by observations of changes in biomass.

Reviewer_1_Minor_Comment_021: L484. "(?), perhaps not" is confusing.

We agreed and removed the referenced text.

Reviewer_1_Minor_Comment_022: L489. Isn't it possible to retrieve the soil moisture as a function of age from the LPJ-wsl output? I had understood that soil moisture was solved independently for each age class.

Soil moisture is solved independently for each age-class, yes. Although we output many state variables by age-class, we currently do not have soil moisture as an output by age-class. We think we understand the Reviewer's point. Such output could be beneficial to a focal analysis or further development of the fire module.

Regarding the context where soil moisture is mentioned in the text, the point we make is that the difference in fire fluxes between the S_{no_age} and S_{age} simulations are probably less to do with soil moisture and more to do with simulating biomass heterogeneity within a grid-cell. After all, each age-class within a grid-cell receives the same exact climate inputs (precipitation, temperature). If it is hot and dry in one age-class, it will typically be hot and dry in all age-classes within a grid-cell.

Reviewer_1_Minor_Comment_023: L493. True, but the apparent large difference for other terms may be just because the scales for most variables do not go to zero in Figure 6. In relative terms they may be comparable to the changes in NEE.

The y-axes are all the same units. Although they are displayed on different scales, the fact that values do not go to zero does not play a role in our interpretation, nor does the relative difference among the state variables. The absolute difference is what matters in this context. It is relevant that there are compensating fluxes from Fire and Rh in the S_{no_age} and S_{age} simulations which contribute to give a similar NEE value.

For clarification -- The compensating fluxes are driven by differences in the distribution of carbon among pools. When we include age-classes in the simulation and see little to no change in global NEE, someone might conclude that there is no important effect of demography. Arguably, carbon stocks in different pools (live vegetation, litter, soil) is easier to benchmark than carbon fluxes from fire or heterotrophic respiration. The differences in the component fluxes and corresponding source stocks are indeed large.

Reviewer_1_Minor_Comment_024: L518. “drier” instead of “dryer”.

Edited accordingly.

Reviewer_1_Minor_Comment_025: L549. The central South America looks as strong as the central USA.

Edited accordingly. The precipitation effect generally tracks semi-arid regions, which was a good sanity check.

Reviewer_1_Minor_Comment_026: L610. Including age dynamics is important, but this is not a novel concept, so it would be nice to put this paragraph into perspective with previous efforts.

We revised sentences in the introduction that puts our work into better context, stating that there are existing models that simulate ecosystem demography.

Reviewer_1_Minor_Comment_027: Fig. 2. In case B, shouldn’t 0.25 be in the 2nd row of the 3rd column, with a zero at the 1st row? Also, can logging be applied to other age-classes or just the last one? If multiple classes can be disturbed, then it may be worth showing such example too (or replacing the single-patch disturbance with a multi-patch disturbance example).

Reviewer_1_Minor_Comment_028: Fig. 4. It would be interesting to compare these trajectories for the two age-class approaches (equal bins, unequal bins).

Reviewer_1_Minor_Comment_029: Fig. 9. These results are a bit surprising given that boreal forests burn frequently. Could this be caused by the zonal averaging, which puts drylands and savannas together with low-disturbance forests in tropical and temperate zones (but not so much in the boreal zone)?

RESPONSE TO REVIEWER #2

Reviewer_2_ Main_Comment_001: The manuscript by Calle and Poulter investigates age-class dynamics as simulated with a dynamic global vegetation model (DGVM) called LPJ-wsl 2.0, a model developed based on the DGVM LPJ. Some aspects of this model are described in the methods, including those which were newly introduced to work with age-classes. The core of the paper seems to be a set of factorial simulations on different spatial scales used to investigate age-class dynamics together with their effect on the simulated carbon fluxes. In addition, the authors assess the contribution of the two types of modelled disturbances (fire vs land use) on forest age structure and derive a generalised linear model to predict carbon fluxes from temperature, precipitation and age-class. The latter is then used to map the “effective range” of each of the predictors to identify regions with significant contribution of demography. I find the manuscript interesting and timely, because forest age structures are an important aspect of the (anthropogenically) disturbed terrestrial biosphere, particularly with respect to the role of land use in climate change mitigation scenarios, and since forest age structures are still underrepresented in DGVMs. In my opinion, however, several aspects of the paper need careful revisions. In particular, the main aim of the paper did not become apparent to me (see general comments below).

Reviewer_2_General_Comment_001: The main aim of the paper is unclear to me and so is what the new aspects are (i.e. the gap mentioned in the abstract l.15 and in the last paragraph of the introduction ~l.81). Is the paper supposed to be a) a model development paper, i.e. describing LPJ-wsl v2.0 or describing the implementation of age-classes in LPJ-wsl v2.0? Or is the paper b) the investigation of the simulated demographic effects? While I find detailed descriptions of models / new model development important and a legitimate scientific contribution, in my opinion, there would still be quite a bit information missing if a) would be the purpose of the paper. To me it especially did not get clear, what has been the new development and what was there before (particularly in subsection 2.2.2 – is this all new or are parts from LPJ-wsl v1.0 or even LPJ?). One aspect that could help to clarify this would be a consequent use of "LPJ-wsl v1.0" vs "LPJ-wsl v2.0" (vs LPJ) highlighting the "modifications for integration with age-classes" (l.118). (Furthermore, there are currently several occurrences of only "LPJ" which probably should be called LPJ-wsl 2.0 (e.g. Table 1, Supplementary, results section)). In addition to having clear model version references, some reordering could help, e.g. moving LPJ-wsl v1.0/LPJ aspects to 2.1.2, such as probably most aspects of fire, primary and secondary/managed forest, LUH2 driver, emissions and residues, product pools, etc. C2 This could, by the way, also solve the sudden occurrence of primary and secondary tiles (l.215) and the unexplained "land use" in Figure 1.

We outline the main aims of the paper in the first sentence of the last paragraph of the Introduction,

> "The overall aims of this study were to present new model developments that simulate the time-evolution of age-class distributions in a global ecosystem model and to determine if explicit representation of demography influenced ecosystem stocks and fluxes at global scales or at the level of a grid-cell."

There are two main aims of the paper. The first aim, (a) to present technical model development details. The ageclass developments are the new developments, which we tried to make clear in the title and abstract. Although the Fire and Land Use modules have not been changed, we described them in detail for completeness because these modules are integral modeled disturbances that initiate ageclasses; detail knowledge of these processes is deemed important, especially if it helps readers identify points of improvement.

We agree that the naming conventions used varied and this is confusing. We replaced all instances of model version to "LPJ-wsl v2.0"

From the current structure of the paper I tend to assume that b) is the main purpose / the new aspect. In this case – but to some degree this also holds for case a) – I would expect some form of comparison to observational based data, particularly for the global simulation for which the authors derive the role of demography in the global carbon cycle.

The second aim of the paper is to (b) demonstrate the effect of ageclass model developments on global scale dynamic vegetation simulations. Aside from showcasing the FIA comparisons to provide confidence that LPJ-wsl v2.0 can reasonably represent forest structure attributes among difference ageclasses, we tried to avoid benchmarking.

Firstly, we demonstrate that ageclass improves structural representation, and that this, in turn affects function, which we show via idealized single-cell simulations. One of the main points of the paper, however, is that the model does not simulate every disturbance. And the disturbances we do simulate (fire, land use change, wood harvest) and need improvement. As such, the results we present underestimates ecosystem ages, and therefore the results underestimate the demographic effect.

It is unclear to us as to how other state variables such as global NPP, GPP, Rh, Fire Flux, etc., would change with a realistic representation of forest ages. A benchmarking effort is beyond the scope of this paper, although we are working toward this end to improve our confidence in the flux estimates.

On one hand, I would expect some kind of comparison of the global simulation with and without age-classes to e.g. a GPP or better AGB dataset to get a feeling for the relevance of the finding of a 40 PgC increase in turnover, and, on the other hand a comparison to a global age map, especially since one of the authors recently published such a map (Poulter et al., 2018). The comparison to a global age map could particularly be instructive to learn where the model fails to reproduce age-structures from the observational based dataset and to discuss why this might be the case (e.g. missing disturbances vs. issues with the fire algorithm or as I expect also issues with the LUH2 data – could be included e.g. in 3.3.2 and 4.1).

We provide a comparison of ecosystem ages in map form and violin plots of ecosystem ages by continent for the GFAD v1.0 age map (Poulter et al. 2018). Much can be learned, even without benchmarking. We know the model underestimates ages because we lack representation of all types of disturbances, from windthrow to beetle kill to small fires. FireMIP results (Hanston et al. 2020 GMDD) clearly demonstrate that the GlobFIRM module we use in LPJ-wsl v2.0 underestimates burned area.

Reviewer_2_General_Comment_002: I had some problems with the way the matrix notation is presented. In general, I found the matrix description a good idea, since it quite nicely visualizes what happens upon ageing and particularly which fractions are merged into the next age-class. My critique, however, is that this is not what has been done in the code and that it also does not suit any of the two age-class setups applied in the study (Table 1). I would therefore recommend to clearly state that this is the theoretical idea, which neither suits the applied age-class setups (because they both contain unequal age widths) nor is what has been implemented in the code. Furthermore, I would appreciate a paragraph on how the age tracking is actually realised in the code.

We added text to clarify that the matrix formulation is the theoretical basis for the approach. In our paper, we offer four different ways of explaining the VTFT method: 1) the mathematical theoretical description, 2) a plain-language summary of the method, 3) a visual description of hypothetical examples in figure form, and 4) we provide the full model code. We understand that our approach is hard to translate so we tried four different ways of presenting the same procedure in an effort to reach the most people. As a programmer, I find it always easiest for me to view the actual code to understand the implementation more completely. In case you are interested, the main block of code is freely available (also on Zenodo):
<https://github.com/benpoulter/LPJwsl_v2.0/blob/master/src/tools/ageclass_transition.c>

Reviewer_2_General_Comment_003: The authors state that the simulated age structures are an "upper limit of ageclass distributions" due to not represented disturbances (e.g. l.38, l.593) and that the study overestimates ecosystem age (l.606). However, couldn't the simulated disturbances (fire, harvest and land-use changes) also be too strong in some places? Especially with l.233-239 stating that "deforestation always occurs in the ranking of oldest to youngest age-classes. . . typically resulting in greater land-to-atmosphere fluxes"? Could this lead to too young forests as well as to an overestimation of historical fluxes?

We removed the term 'upper limit' throughout. We added clarifying text as below.

"In some locations, it is possible that our wood harvest priority rules (harvest oldest age-class first) might lead to simulated stand ages that are younger than observed stand ages if other harvest rules were applied in practice, such as preferentially logging forests of intermediate age with a goal of preserving the oldest forests from harvest. We evaluated the age distribution by continent simulated by LPJ-wsl v2.0 to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data (SM Figure 11). The comparison shows that the simulated ages are consistently older than the GFAD dataset."

The GlobFIRM fire module clearly underestimates burned area, see results from fire-model inter-comparisons from FireMIP (Hanston et al. 2020); we have updated the Hanston et al. 2017 reference to the 2020 paper throughout. The FireMIP results confirms similar findings about GlobFIRM.

For the conclusions drawn in this manuscript, two additional scenarios could maybe be valuable: a) a simulation with deforestation occurring in the ranking from younger to older age-classes and b) a "best guess" simulation using the LUH2 harvest categories "harvest from secondary young forest" and "harvest from secondary mature forest".

Certainly, there are scenarios where we will want to identify regional logging practices for which these encoded rules can be modified. That would be interesting, especially for a focal analysis on full cycle sustainable harvest practices. For simplicity and to reduce the number of 'moving targets', we chose to stay with the old-to-young harvest assumption.

Another thought: Have the authors considered conducting the fully fledged global simulation also with the unequal bin setup? Would this lead to different results?

It is possible this would lead to different results, but most likely only in an extreme 'very young world' scenario, or in the 'fire band' latitudinal zones, where the ecosystems are relatively young. That's an interesting point, however, and a case to be made for a more flexible setup, such that the ageclass setup could be flexible to accommodate more frequent disturbances. In any case, the largest differences in ecosystem function (NPP, Rh) between the two ageclass setups (equal/unequal binning) are seen in the youngest ageclasses.

Reviewer_2_General_Comment_004: Literature work: In some of the sections I had the feeling that more references / locating the paper in context of the existing literature would be appropriate.

a) First of all I wondered if LPJ-wsl v2.0 is the model on which the publication of Pugh et al. (2019a) is based? In this case this should in my opinion clearly be stated in the paper.

Agreed. We added clarifying text as below for transparency.

"Technical details are presented for a module representing age-class dynamics, driven by fire feedbacks, land abandonment and wood harvesting in the LPJ-wsl v2.0 Dynamic Global Vegetation Model (DGVM). Prior versions of LPJ-wsl v2.0 that included early technical developments of the land use change module and the age-class module have already contributed to prior studies (Arneth et a. 2017, Kondo et al. 2018, Pugh et al. 2019a).

b) Looking in the literature for occurrences of LPJ-wsl I found several publications that had at least short model descriptions and I wonder why none of these is referred to in the manuscript (e.g. Poulter et al, 2015; Zhang et al. 2017,2018)?

We understand the confusion. The unique feature of LPJ-wsl v2.0, including earlier versions of LPJ-wsl (as referenced above), is that it is programmed as a fully modular model. Each module can be run independently using compiler flags. This is slightly different than other DGVM models. We have maintained a practice of preserving old code (bug-free) and adding modular updates to process representation, such that we can revert to older versions of the code. Poulter et al. 2015 does not present model developments. Modular developments for permafrost and wetland methane by Zhang et al. 2017,2018 are not 'turned on' and do not influence our simulation results. At some point, our goal is to conduct a full factorial experiment with all the modular developments, but this is not the aim of this paper.

c) In section 2.2.1 l.142 when introducing the VTFT approach, the authors point to the paper by Nabel et al. (2019) having a similar independently conceived approach. Indeed, it seems as if many of the aspects described in 2.2.1 are similar to those described in Nabel et al. (2019), including the tracking of fractions per year and the merging process: merging of disturbed areas into the youngest age-class and merging of aging fractions exceeding the width of the age-class into the next age-class. Each with subsequent area-weighted averaging of carbon with the transitioning fractions. To a certain degree similarities seem to also hold for the applied age-class setups. While I truly believe that this approach has been independently conceived, I would still recommend relating to the existing approach, e.g. pointing out similarities and in particular also differences.

We added the following text below to the corresponding Section 2.2.1. We clearly state in the text that the VTFT method is similar to that described in Nabel et al. 2020. "The most novel advancement in this study is a new method of age-class transition modeling, which we call 'vector-tracking of fractional transitions' (VTFT), which improves the computational efficiency of modeling age-classes in global models; this is a similar approach independently conceived by Nabel et al. (2019). ". Their paper only provide a brief description of their method. Their focus appears to be on the implications of different age width binning in age class simulations. We add the following text that draws on their findings.

"The age widths of the age-classes in the *10yr-equalbin* setup correspond to common age widths of classes used in forest inventories; for contrast, JSBACH4 uses a 15-year age width in their equal-bin ageclass setup. Most ageclasses in this setup are represented by a vector of 10 elements, wherein each element represents an aerial fraction for each age-unit (Table1)."

A study by Nabel et al. (2020), using the demographically-enabled JSBACH4 DGVM, found that unequal binning of age widths had lower errors than equal age width binning but the largest reduction in model-observation error was achieved by simply adding more ageclasses at younger ages, regardless of the binning strategy employed.

Reviewer_2_General_Comment_005: I would recommend clearly stating when simulation output is referred to as opposed to observational based data (e.g. l.20, l.32-33).

Edited accordingly.

Reviewer_2_General_Comment_006: It did not become clear to me what exactly is compared in 2.3.2 and 3.1: Are these simulation results from a global simulation? From which? Sage? But if from Sage, why are the FIA data with disturbance, stocking or longing excluded?

Reviewer_2_General_Comment_007: Figure 3 and 4: I would appreciate to also have Figure 4 for the 10-year age-widths, since this is what is used in the global simulations. Also, could for ease of readability maybe all panels with unequal age-widths start with the youngest age-class? Furthermore, it might increase comparability when changing the x-axis to show linearly increasing years instead of the classes and then to place the boxes for the different age-classes at age-class mean ages. This would particularly underline the differences in the NEP dynamics among the different age-class setups. Even more so, if the two age-class setups would be integrated in one plot/panel for each of the depicted variables instead of having separate panels with differing x-axis.

Reviewer_2_General_Comment_008: Is there a recommendation/conclusion on what age-class setup to use based on the studied simulations? I.e. when would a simulation with unequal bins be preferable, when with equal bins or the like?

> We clarified in Section "2.2.1 An age-based model of ecosystems – sub-grid-cell dynamics" as below. We think this provides recommendation to use equal-bin setup for global simulations.
>
> "... The within-ageclass elements are not independent and every within-ageclass element has the same state variables, including the same soil water and light. As such, we only simulate processes at the ageclass level, and the within-ageclass elements are a simple method for a 'smooth' transition between ageclass. In theory, we can simulate processes independently for each within-ageclass element, but this is not practical or necessary. The main benefit for using equal-bin or unequal-bin ageclasses is to independently simulate processes. ..."
>
> ".. The use of equal or unequal age class setups is more than just for reporting purposes. There resources differ between age-classes but not within age-classes, and we limit the model to represent a total of 12 ageclasses. Also, there exists a greater range of forest ages at global scales and the equal age-class setup allows us to independently model resource dynamics (space, light, water availability) for more of the terrestrial surface. If we had chosen the unequal-bin setup for global simulations, we would be independently modeling processes only for the youngest age-classes and we would lose capacity to independently model processes at intermediate and older age-classes."

Specific comments/ Technical corrections: —– - Mixed usage of hyphens: grid cell, grid-cell, gridcell; age-widths, age widths; age class, age-class; land use change -> land-use change; land use transitions -> landuse transitions; land-use -> land use, . . .

> We changed 'grid-cell' to 'grid cell' throughout, except when it was used as a joint adjective.
>
> We changed 'age-width' to 'age width' throughout, except when it was used as a joint adjective to describe the bins.
>
> We changed 'land use change' to 'land-use change' throughout.
>
> We changed 'land use transitions' to 'land-use transitions.
>
> We verified that 'land use' was used appropriately to describe the use of the land.

Reviewer_2_Technical_Comment_001: l.13 "most global ecosystem models" – consider changing to "many" acknowledging the considerable list in l.55-57.

Edited accordingly.

Reviewer_2_Technical_Comment_002: l.15 Could you specify which gap exactly?

We changed the phrasing as below.

".. This paper aims to present the technical developments of a computationally-efficient approach for representing age-class dynamics within a global ecosystem model, the LPJ-wsl v2.0 Dynamic Global Vegetation Model, and to determine if explicit representation of demography influenced ecosystem stocks and fluxes at global scales or at the level of a grid-cell. .."

Reviewer_2_Technical_Comment_003: l.18 Could you maybe make this sentence a bit more precise? Could it also be fractions of an age-class which experience a stand-clearing disturbance? The simulated stand clearing disturbance is fire, and the prescribed ones are harvest and abandonment of agricultural area?

A disturbance can occur on a fraction of an age-class, yes.

We rephrased for clarity as below.

".. The modeled age-classes are initially created by simulated fire, and prescribed wood harvesting or abandonment of managed land, otherwise aging naturally until an additional disturbance is simulated or prescribed. .."

Reviewer_2_Technical_Comment_004: l.20 "that patterns of ecosystem function" -> simulated patterns? Patterns resulting in/from model simulations?

We added clarifying text throughout to specify whether a statement refers to simulated or observed data, as in ".. that **simulated** patterns of ecosystem function .."

Reviewer_2_Technical_Comment_005: l.24 land-use change

Edited accordingly.

Reviewer_2_Technical_Comment_006: l.25 "an additional" –in the sentence before, with regards to fire, only the difference between boreal and tropical lats is given, maybe you could give the absolute effect there, too?

We removed the wording 'additional' and simply stated that "Between simulation years 1860 and 2016, land-use change and land management were responsible.."

Reviewer_2_Technical_Comment_007: l.25 "-21 years in temperate (23N-50N) and tropical latitudes" are these analysed together or independently but experience both the same decrease in age through landuse change and land management?

Temperate and Tropical latitudes were analyzed separately, see results of the statistical model presented in Table 3. But yes, they experienced the same decrease in age over time as a result of land use change and land management

Reviewer_2_Technical_Comment_008: l.32-33 please clarify what kind of "Spatial datasets are provided for global ecosystem age" simulated ones? Do these stem from the 'fully-fledged' LPJ-wsl v2.0 simulations?

We clarified as below. (bold for emphasis, here only)

"..**Simulated** spatial datasets are provided for global ecosystem age..". Yes, these simulated datasets stem from the LPJ-wsl v2.0 age-class simulations, with simulated fire and prescribed land use change and wood harvest,

Reviewer_2_Technical_Comment_009: l.35 "40-Pg C" -> "40 Pg C"

Edited accordingly.

Reviewer_2_Technical_Comment_010: l.35-36 A 40 Pg C increase over which time period?

Over the full simulation period the live biomass carbon in the no_age simulation is greater by ~40 Pg C, as compared to the age-class simulation. In the age-class simulation, there soil carbon is greater by ~33 Pg C and litter carbon greater by ~7 Pg C, as compared to the no_age simulation.

We revised as below. (bold for emphasis, here only).

"..and a finding of a 40 Pg C increase **in biomass turnover when including age dynamics** at global scales.."

Reviewer_2_Technical_Comment_011: l.38 "upper limit" – what do you mean with upper limit? That the forest will not be younger? Please consider rephrasing/explaining. And couldn't the modelled disturbances (fire, harvest and land-use changes) also be too strong in some grid-cells leading to forest which is too young (particularly due to the applied old forest first rule; see also general comments)?

We removed the term 'upper limit' throughout. We added clarifying text as below.

We edited the sentence in the abstract to the following, "The LPJ-wsl v2.0 age-module represents another step forward towards understanding the role of demography in global ecosystems."

We added the following text in the Discussion, "In some locations, it is possible that our wood harvest priority rules (harvest oldest age-class first) might lead to simulated stand ages that are younger than observed stand ages if other harvest rules were applied in practice, such as preferentially logging forests of intermediate age with a goal of preserving the oldest forests from harvest. We evaluated the age distribution by continent simulated by LPJ-wsl v2.0 to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data (SM Figure 11). The comparison shows that the simulated ages are consistently older than the GFAD dataset."

Note that the GlobFIRM fire module definitively underestimates burned area, see data for fire-model intercomparisons from FireMIP (Hanston et al. 2020); we have updated the Hanston et al. 2017 reference to the 2020 paper throughout. The FireMIP results confirms similar findings about GlobFIRM.

Reviewer_2_Technical_Comment_012: l.41-45 this seems to rather be an enumeration than a sentence and pretty long, could it maybe be taken apart and rephrased?

We edited as suggested.

Reviewer_2_Technical_Comment_013: l.49-52 This sentence seems imprecise to me: From which of the publication exactly do the ~60% total sink stem from? Over which time period? What are the time periods for which Pan et al. 2011b and Pugh et al. 2019a report/estimate the specified sinks, respectively? Is this in combination with changes in environmental forcings?

60% is an approximation as to the role of regrowth in the global land carbon sink. It is correct to suggest that this is not a settle estimate. We edited the text as below to provide greater clarity.

"On global scales, forest age is a considerable factor in global carbon cycle and comprises a large fraction of the total land carbon sink, which is estimated at 3.2 ± 0.8 Pg C yr^{-1} for years 2008-2017 (Le Quere et al. 2018). According to country-level forest inventories, net carbon uptake from post-disturbance tropical forest regrowth is 1.6 ± 0.5 Pg C yr^{-1} from 1990 to 2007 (Pan et al. 2011a). Although the timeframes for estimates of the total lank sink and the inventory regrowth flux do not perfectly overlap, the magnitude of the regrowth sink relative to the total land sink warrants that models take regrowth dynamics into account. A multi-model global regrowth analysis with demographically-enabled DGVMs, for which LPJ-wsl v2.0 contributed, estimated that post-disturbance regrowth comprised a large global regrowth sink of 0.3 to 1.1 Pg C yr^{-1} due to demography alone over years 1981-2010 (Pugh et al. 2019a)."

Reviewer_2_Technical_Comment_014: l.50 Pan et al. 2011b not 2011a according to the references?

Correct. The Pan et al. references have been reordered so that 2011a comes first in the text. The references have been updated throughout.

Reviewer_2_Technical_Comment_015: l.51 really 0.3 to 1.1 PgCyr-1?

Yes.

Reviewer_2_Technical_Comment_016: l.51 When I understood it correctly than the findings in Pugh et al. 2019a are mainly build on exactly the model being described in this study? In this case I would find the line of argumentation circular, in-transparent and therefore somehow scientifically concerning.

Yes, a version of the age-module was applied in Pugh et al. 2019a. This is now stated for transparency. The age-module was never fully described or presented elsewhere previously.

Reviewer_2_Technical_Comment_017: l.54 why is fire listed separately of "disturbances"?

In the line referenced, we removed the term 'disturbances' and simply stated '..land use change and land management, and fire ..'

Reviewer_2_Technical_Comment_018: l.60 but have a look at e.g. Zaehle et al. (2006) or Bellassen et al. (2010)

Following a similar comment from Reviewer #1, we rephrased as below.

"... Following a call to the science community to improve demographic representation in models (Fisher et al. 2015), there is now a growing list of global models that are capable of simulating global ecosystem demographics (Gitz and Ciais 2003, *Model*: OSCAR; Shevliakova et al. 2009, *Model*: LM3V; Haverd et al. 2014, *Model*: CABLE-POP; Lindeskog et al. 2013, *Model*: LPJ-GUESS; Yue et al. 2018, *Model*: ORCHIDEE MICT; Nabel et al. 2019, *Model*: JSBACH4), although more models need the capability to represent landscape heterogeneity in forest structure and function. ..."

Reviewer_2_Technical_Comment_019: l.64-65: Unfortunately, I cannot find this order in Frolking et al. (2009). In section 3.1 in Frolking et al. (2009) globally disturbed fire area is largest (∼3 × 106 km2 a−1) but only 1 × 105 km2 a−1 in forest – which is equal to that estimated for wind (∼1 × 105 km2 a−1), while global estimates for wood harvest and shifting cultivation are larger–each ∼1–2 × 105 km2 a−1 of forest area.

We removed the sentence from the text. We were referring to general disturbances over all ecosystems. The reviewer is correct in the Frolking reference.

Reviewer_2_Technical_Comment_018: l.76-79: Please clarify: why forest management here – elsewhere land-use change and land management?

Edited text, changed 'forest management' to 'LUCLM'

Reviewer_2_Technical_Comment_020: l.81 Could you specify which gap exactly? Else maybe omit this phrase?

The sentence was rephrased as below.

"The overall aims of this study are to present new model developments that simulate the time-evolution of age-class distributions in a global ecosystem model and ..."

Reviewer_2_Technical_Comment_021: l.81-83: Note: Several of the studies listed in l.55-57 have demonstrated that a representation of demography influences ecosystem stocks and/or fluxes.

We changed the text to clarify as below. (bold for emphasis, here only).

"...to determine if explicit representation of demography **in this model** influenced ecosystem stocks and fluxes..."

Reviewer_2_Technical_Comment_022: l.85 is there any more recent reference than Sitch et al. 2003 (maybe Poulter et al, 2015; Zhang et al. 2017,2018)? Or maybe rephrase e.g. "a model building/based on the Lund..."?

Sitch et al. 2001 is the main reference for the LPJ model. Bondeau et al. (2007) provide technical details for additional advancements, namely the agriculture module, but we do not use the agriculture module in this paper. The development history is described in Section "2.1.1 LPJ History"

Reviewer_2_Technical_Comment_023: l.110 are?

Edited accordingly.

Reviewer_2_Technical_Comment_024: l.115 before and elsewhere in the text I understood that fire is also implemented as a stand replacing disturbance/ burned fraction moves to youngest age-class?

For clarity, we changed two mentions of 'stand replacement' or 'stand-clearing' in the text as below.

".. Although pest and pathogens, namely bark beetle infestations, affected a much larger area (up to 6% of total forested area in U.S.) than both logging and fire, their effects do not always cause ~~stand replacement~~ immediate tree mortality. .."

".. Not all trees are killed-off when a ~~stand-clearing~~ disturbance occurs in LPJ. ..."

Reviewer_2_Technical_Comment_025: l.130 "unequalbin setup is applied to explore model dynamics at the level of a single grid-cell;" according to Table2 its not a single grid-cell but region, which is also suggested by e.g. Fig.4.

We edited the text as below.

".. The *10yr-equal*bin age setup is used for all simulations including the global simulation, whereas the *unequalbin* setup is used for regional and single grid cell simulations; simulation details in next section. ..."

Reviewer_2_Technical_Comment_026: l.127-131: I would appreciate a bit more information on and explanation of the choices that drove the separation in age-classes. Particularly, why is the cut off with 151years in the 10-yr equal bins and why is it with 101years in the unequal bins? Why is the age range of the pre-last class (code 11) in the 10-yr equal bin larger – making it an "unequal bin", too. Maybe also the motivation for the 2, 5 and 25 year ranges as well as the switches between these ranges could shortly be outlined? If this resulted e.g. from preliminary tests, the experiences of the authors could maybe be instructive to the readers.

The binning was chosen to align with U.S. forest inventory data and we wanted greater resolution in the age-classes between 1-100. The unequal-bin setup was primarily implemented to evaluate issues with the equal-bin setup. We did not explore other binning methods as we were satisfied that the equal-bin setup was sufficient. We added text to clarify why we use the 10-year equal bin setup for global simulations as below.

".. The use of equal or unequal age class setups is more than just for reporting purposes. Resources available to plants (space, light, soil water) differ between age-classes but not within age-classes, and we limit the model to represent a total of 12 ageclasses only. Also, there exists a greater range of forest ages at global scales and the equal age-class setup allows us to independently model resource dynamics for more of the terrestrial surface. If we had chosen the unequal-bin setup for global simulations, we would be independently modeling processes only for the youngest age-classes and we would lose capacity to independently model processes at intermediate and older age-classes. .."

Reviewer_2_Technical_Comment_027: l.146 . . . number "of" simulated . . .

Edited accordingly.

Reviewer_2_Technical_Comment_028: l.161 I would recommend to introduce a j on the w to indicate that the age-classes (can) have different widths EQ4 and l.173 personally I find f0,0 an unlucky choice and would prefer an extra term, such as fdis or the like EQ5 and l.179 why a capital F in F(t)_w,j-1, isn't this just one entry?

We changed f0,0 to f_{new} clarity. Yes we reference a single element; we changed the text accordingly to $f_{w,j-1}^{(t)}$

We revised Equation 2 to show that the sum of fractional areas for all patches in a grid cell is defined by the sum of fractional areas for all age classes and age widths.

Reviewer_2_Technical_Comment_029: l.192-199: is this an enumeration? If so, could it maybe be separated with newlines? Else I would appreciate complete sentences.

Prior text in reference "Within-class Fractional Transitions: For every simulation year, the position of each element (fx) in the VTFT vector is incremented by the representative time of each element (x), which is simply 1. No changes occur to the state variables of the age-class during within-class transitions. Between-class Fractional Transitions: Upon incre195 menting the position of each element, if the value at (fw) is non-zero, then the corresponding fractional area fw, defined as the outgoing fraction, is used in an area-weighted average between the state variables of a1 fw and the next oldest age-class a2 F_total. Lastly, upon incrementing element position, if all elements < f1 ... fw > in the VTFT vector of the preceding age-class, in this example (a1), are zeros, then the age-class is simply deleted from computational memory."

Text above changed as below, with

"The following is a description for within-class and between-class transitions. *Within-class Fractional Transitions*: For every simulation year, the position of each element (f_x) in the VTFT vector is incremented by the representative time of each element (x), which is simply 1. No changes occur to the state variables of the age-class during within-class transitions. *Between-class Fractional Transitions*: Upon incrementing the position of each element in the VTFT vector, if the value at f_w is non-zero then the corresponding fractional area (f_w), defined as the outgoing fraction, is used in an area-weighted average between the state variables of a_1 *fw* and the next oldest age-class a_2 *F_total*. Upon incrementing element position, if all elements in the VTFT vector of the preceding age-class are zeros then the age-class is simply deleted from computational memory."

Reviewer_2_Technical_Comment_030: l.202 to which age-widths does this refer to, those from the unequal setup or both setups? Is there a specific section of the manuscript where "it is demonstrated" or is this a more general statement as "in this study"?

The text was edited for clarity, as below.

"Two hypothetical scenarios are provided in Figure 2 that demonstrate age-class transitions using the VTFT procedure when there is a young age-class created, and when there are fractional age-class transitions between age-classes. With VTFT, any number of age-classes and age-widths can be modeled, but it is demonstrated in this study that ..."

Reviewer_2_Technical_Comment_031: l.206 and 220 "merged with a youngest" -> the? Or can there be several youngest?

'youngest' is use in the singular, I'm not sure there is a plural interpretation to the word. For plural, one might say the 'young' ageclasses.

Reviewer_2_Technical_Comment_032: l.213 I do not understand this, why can't the not burning fraction stay in the current age-class/patch and only the burned fraction move to the youngest age-class?

Only the fraction that burns gets moved to the youngest age-class. The fraction that does not burn stays in the current age-class. The text (L 213) refers to the PFT population that does not burn completely and kill-off all the trees. The simulated burned fraction may have surviving trees.

Reviewer_2_Technical_Comment_033: l.215 This is the first time primary and secondary forest are mentioned. Also, the term tile has only been mentioned one time before ("Age-classes are represented as subtiles within a grid-cell"). Maybe it would help to already introduce these aspects in 2.1.1?

Removed the sentences below.

~~Fire can occur in both the primary forest and secondary forest tiles; the classification of primary versus secondary forests is determined by the land use driver dataset~~

We have replaced most instances of 'patch' and 'tile' with simply 'age-class' throughout.

Reviewer_2_Technical_Comment_034: l.217 Does managed land refers to crop/pasture here (i.e. not forest management)?

Yes. Text edited for clarity as below.

"Age-classes get created when managed land (i.e., crop/pasture) is abandoned..."

Reviewer_2_Technical_Comment_035: l.225-226 mix of singular and plural?

'give' changed to 'gives'.

Reviewer_2_Technical_Comment_036: l.224 I assume this is not a only "if the". Consider rephrasing such that it gets apparent that net zero land-use change is just one example?

Not sure I understand the Reviewer's comment, but we edited the text as below.

"In the LUCLM module, gross transitions between land uses are simulated (Pongratz et al. 2014, Stocker et al. 2014), such that if the fraction of abandoned land equals the fraction of land deforested in the same year (net zero land use change) then the fluxes from the gross transitions are tracked independently and give an overall more accurate accounting (and higher magnitude) of emissions from LUC than if we only tracked net transitions. ..."

Reviewer_2_Technical_Comment_037: l.229, l.263, l.527, l.602 consider updating to Hurtt et al. 2020 l.228 lost "and"?

The citations were updated to Hurtt et al. 2020 as suggested.

Reviewer_2_Technical_Comment_038: l.229: I do not understand what you mean with modifications 1a (and 2a) seem not to be modified with respect to LUH2?

The text was updated for clarity, as below.

"... but with the following modifications so that the LUHv2 data can be used in LPJ-wsl v2.0: ..."

Reviewer_2_Technical_Comment_039: l.233: LUH2 offers a separation of harvest to mature and young forests. Consider shortly stating why this separation is not used in LPJ-wsl 2.0?

LUHv2 does not provide distinction of stand age at finer granularity other than 'young' and 'mature'.

Reviewer_2_Technical_Comment_040: l.233-237: But wouldn't e.g. shifting cultivation rather make use of younger forests?

It is possible, yes.

Reviewer_2_Technical_Comment_041: l.237-238: LUH2 offers both, harvested area and harvested biomass. Here it is stated: "until two conditions are met" and in the next sentence: "until a prescribed harvest mass or harvested area is met". This requires clarification when which of these criteria is applied.

(1b) refers to land-use change, and land-use change is prescribed by an areal fraction. We clarified as follows, "(1b) For simplicity, deforestation (i.e., land-use change) .."

(2b) refers to wood harvest, and wood harvest is prescribed by an areal fraction and the biomass harvested on that fraction. We clarified as follows, "(2b) wood harvest (i.e., biomass harvest) also occurs in the ranking of oldest to youngest age-class ..."

Reviewer_2_Technical_Comment_042: l.244-245: I wonder if this would really be the case, I would assume that the ranking from old to younger age-classes decouples deforestation and abandonment?

The text (L 244-245) refers to a computational issue involved when modeling gross transitions. In a single year, crop/pasture can be abandoned (converted to secondary forest) and forest can be converted to crop/pasture. The order in which these processes are simulated will introduce a bias, or more aptly a model artefact.

Reviewer_2_Technical_Comment_043: l.240-. . . Is this new in LPJ-wsl 2.0 or is this as it has been done already before? Noticing Earles et al (2012)and McGuire et al. (2001) in 249/251 I wondered if the authors could also give the reference for the % ratios in l.240-247?

This is new in LPJ-wsl v2.0. The reference for Earles et al. (2020) is with regard to the concept of delayed emissions. The 40:60 rations are from McGuire et al. (2001), as referenced.

Reviewer_2_Technical_Comment_044: l.249-251: could you clarify which numbers are from Earles?

See above.

Reviewer_2_Technical_Comment_045: l.251-256: "product pool" is used twice here – with different meanings?

We think they have the same meanings. In the literal sense, 'product pool' means 'pooling products'. Another way of interpreting it would be 'carbon stock in [wood] products', or 'storage container for carbon products'.

Reviewer_2_Technical_Comment_046: l.253 “dataset described further in Sect 2.3.3” – I cannot find such a description there?

We removed the text “ ~~dataset described further in Sect. *2.3.*~~”

Reviewer_2_Technical_Comment_047: l.265 “managed lands” = agricultural managed lands (since forests can also be managed?)

‘Managed land’ has different meanings in reference to LUHv2. We specify in the following sentence in the text that “In LPJ-wsl v2.0, managed lands (i.e., crop/pasture) are treated as grasslands with no irrigation, no fire, and tree PFTs were not allowed to establish.”

Reviewer_2_Technical_Comment_048: l.271 “accessed . . .” consider moving to references.

We decided to kept as is.

Reviewer_2_Technical_Comment_049: l.272 “fuzzed” is this relevant for this study?

Yes.

Reviewer_2_Technical_Comment_050: l.275 Refer to SM2 here.

Edited accordingly.

Reviewer_2_Technical_Comment_051: l.275 “model-observation comparisons” – isn’t the model resolution anyway 0.5◦ in the compared simulations?

Yes. By aggregating the plot data to larger domains (USFS Divisions) we intended to reduce the potential influence of differing climate, soils, and location between simulated data and the observations. Such aggregation has been done before for similar reasons, see Purves et al. 2008 PNAS and its supplementary materials.

Reviewer_2_Technical_Comment_052: l.310 and regrowth?

We left as is.

Reviewer_2_Technical_Comment_053: l.318 info does not match Table 2.

Yes it does. Section 2.3.4 refers to the single-cell simulation, not the Regional simulation.

Reviewer_2_Technical_Comment_054: l.320 it is unclear to me which of the deforestation rules from Section 2.2.2. also applies for the Snoage_event simulation, could you please give a bit more detail?

We rephrased as below for clarity.

“Treatment of deforestation byproducts (i.e., carbon in dead wood left on-site) were the same in both simulations.”

Reviewer_2_Technical_Comment_055: l.322 NBP so far not introduced (NPP and Rh only in the abstract).

We clarified the text as follows, “Net Biome Production (NBP, defined as NBP = NEP – LUC_flux)”

Reviewer_2_Technical_Comment_056: l.330 Table lists 4 objectives/questions.

We edited the text accordingly, as below.

“The third and fourth objectives used data from $\mathbf{S}_{age}$ to determine where the effect of demography was greatest and to identify the relative influence of demography versus climate on simulated fluxes (NEP, NPP, and Rh).”

Reviewer_2_Technical_Comment_057: l.336 Maybe already add here for clarification that Sage = SFireLU.

Edited accordingly.

Reviewer_2_Technical_Comment_058: l.339 “all three simulations” presumably refers to SFire, SLU and SFireLU? But what about Snoage? What was the spin-up procedure for this simulation?

We edited the text to clarify as follows, “For all global simulations..”

Reviewer_2_Technical_Comment_059: l.339 does the first spin-up also has “land use values” or does it assumes only natural vegetation?

We clarified as follows, “a spinup simulation...and no land use or wood harvest...”

Reviewer_2_Technical_Comment_060: l.341 Could you please specify what you mean by ‘natural conditions’ – fire?

Some of the simulations had fire turned-off. We removed the text in reference (‘natural conditions’) and the sentence now reads as follows, “..spinup ensured that age distributions and state variables were in dynamic equilibrium (i.e., no trend).”

Reviewer_2_Technical_Comment_061: l.342 please clarify “land use values” does that mean managed agricultural land distribution? What about harvest?

We restated for clarity as below, “..to initialize land use fractions of crop/pasture to year 1860..”. Wood harvest was not simulated during spinup procedures.

Reviewer_2_Technical_Comment_062: l.342 please clarify: was the second spin-up procedure subsequently or alternatively for different simulations? Do all four simulations start from the same values in 1860?

Only simulations that used land use had a second spinup procedure. We edited the text to clarify as follows, “For simulations with land use, a second ‘land-use-spinup’..”

Reviewer_2_Technical_Comment_063: l.356-359 I found this sentence a bit difficult to read since the “By contrast, fire . . .” seems to refer to the “Trends in LULCM are . . . prescribed” – please clarify by e.g. rephrasing.

Yes, “By contrast, fire is a fully simulated process . . .” does refer to the “Trends in LULCM are . . . prescribed”. We rephrased for clarity as below.

“Trends in age distributions due to LUCLM are not prescribed by inputs per se; instead, the age module is a necessary model structure that allows full realization of the effect of forcing data on age distributions. Trends in age distribution due to Fire, which is a simulated process as opposed to prescribed, result from climate and fuel load feedbacks on fire simulation.”

Reviewer_2_Technical_Comment_064: EQ6 I wonder if the last factor should be written as a sum with age classes as index?

The equation was edited as below, with the ‘age’ subscript in the ageclass term removed.

$$flux_{i,yr} = B1_i \times \text{total\_precipitation}_{i,yr} + B2_i \times \text{mean\_temperature}_{i,yr} + B3_{i,ageclass} \times ageclass_{i,yr}$$

In any manner the last term in Eq #6 is correct, it is not a sum. In the equation, the indices refer to how the terms vary. In the case of the last term in the equation, $B3_{i,age} \times ageclass_{i,yr}$, the beta coefficient (B3) vary as a function of grid cell (i) and ageclass code (*ageclass*). The ageclass code can vary as a function of grid cell (i), year (yr).

Reviewer_2_Technical_Comment_065: l.393 “age-structure patterns” – maybe “patterns of tree density and height per age”?

Yes, that was the meaning. We edited the text accordingly.

Reviewer_2_Technical_Comment_066: l.397 what does stand refers to –patch?

Yes. ‘patch’ changed to ‘age-class’ for consistency.

Reviewer_2_Technical_Comment_067: l.404 I do not understand this part of the sentence: “data be taken on every species; although species-level data are available”.

The paragraph has been edited for clarity of meaning. The updated text is below.

“FIA data had greater variability among age-classes, regardless of Division. FIA data are not aggregated by PFT, instead they are species-level data. Changes in species composition over time do occur and it can add to the observed variability among age-classes in tree density and tree height. LPJ-wsl v2.0 includes a limited set of PFTs, which most likely limits the model’s capacity to represent similar levels of variation in tree density and tree height. It is beyond the scope of this study to disentangle these patterns further, but greater agreement between observed and simulated patterns of forest structure might be acheived by including additional plant functional types that are representative of tree species for a given Division.”

Reviewer_2_Technical_Comment_068: l.417 These survivor trees make me think if a classification as “time since disturbance” would make more sense than a classification as age-classes?

We maintain that the ‘age-class’ terminology is the correct terminology to use. Stand age (‘age-class’) is typically used to explain consistent and predictable patterns of ecosystem function and forest structure with stand age, survivor trees notwithstanding.

In the simulations, survivor trees represent a very small fraction of the PFT population. In Figure 3, the survivor trees are evident in lowest age-class of the tree height plot for the unequal-bin simulation setup. The corresponding tree density in the lowest age-class is very low. Survivor trees are likely also present in the equal-bin setup, but the patterns for tree density and tree height are not affected.

Reviewer_2_Technical_Comment_069: l.417 LPJ? LPJ-wsl 1.0? LPJ-wsl2.0? All of them?

For consistency, we changed all references to the current model to LPJ-wsl v2.0.

Reviewer_2_Technical_Comment_070: l.442 all “three” U.S. States.

No, not ‘three’ states, but *all* states. The text in reference (L 442) refers the consistent and predictable pattern of NEP as a function of age. We estimated the exponent using data pooled over all states, and separately using data from each state. The exponent value was consistent.

Reviewer_2_Technical_Comment_071: l.452 Figure 5?

Yes. The text was edited accordingly.

Reviewer_2_Technical_Comment_072: l.457 missing t in event.

We cannot find the typographic error in question.

Reviewer_2_Technical_Comment_073: l.457 LPJ? LPJ-wsl 1.0? LPJ-wsl2.0? All of them?

We changed all references to the current model to ‘LPJ-wsl v2.0’.

Reviewer_2_Technical_Comment_074: l.484 “(?)”?

We edited the sentenced reference as follows, “The question still remains – should there be an expectation for greater differences in NEE?”

Reviewer_2_Technical_Comment_075: l.487 Snosge -> Snoage

Edited accordingly.

Reviewer_2_Technical_Comment_076: l.498 LPJ? LPJ-wsl 1.0? LPJ-wsl2.0? All of them?

We changed all references to the current model to ‘LPJ-wsl v2.0’.

Reviewer_2_Technical_Comment_077: l.508-509 the 23 years are not directly evident from Table 3, nor is it the decrease in zonal ecosystem age, could you help your readers specifying which of the values in Table 3 show these? This also holds for the rest of the paragraph; maybe consider extending Table 3 or adding another table showing integrated values?

We rewrote the paragraph to clarify as below. Originally, we arrived at the '23 year' difference in ages by expanding the statistical model to estimate the ecosystem age in year 1 (simulation year 1860). As an example, the age in year 1 for Boreal latitudes is given by $(141.7-(0.0098*1)) = 141.6$, the age in year 1 for Temperate latitudes is given by $(118.5-(0.0525*1)) = 118.4$, and the difference is given by $141.6 - 118.4 = 23.2$ [years]. To arrive at the age estimated in the simulation year 2016, the year index is 157, so the age would be given by $(141.7-(0.0098*157)) = 140.1614$.

"Ecosystem age by zonal band was oldest at boreal latitudes, followed by temperature latitudes, and youngest in tropical latitudes, which was primarily the results of frequent fires in simulated grassland ecosystems. The primary driver of zonal age distributions was Fire (Figure 8). According to results from the statistical model (Table 3), the average age difference due to fire among zonal bands in 1860 was 23 years between Boreal (older) and Temperature (younger) latitudes, and it was 32 years between temperature (older) and tropical (younger) latitudes. The difference in ecosystem age among zonal bands increased to 60 years in simulation year 2016 between boreal and temperate latitudes, while the difference in ages between temperature and tropical latitudes remained similar (31 yr age difference). There was a statistically significant decrease in zonal ecosystem age over time due to fire (Table 3)"

Reviewer_2_Technical_Comment_078: l.519 grammar issue?

Not sure we understand the Reviewer's concern with the sentence in question.

Reviewer_2_Technical_Comment_079: l.529 also here sum over B3age?

No, there is no summation in the statistical model.

Reviewer_2_Technical_Comment_080: l.530 simulated NPP and Rh.

Yes, we added 'simulated' to clarify we mean the simulated NPP and Rh.

Reviewer_2_Technical_Comment_081: l.533 consider to delete "slightly"!

Edited accordingly. The difference is more than 'slight', thanks.

Reviewer_2_Technical_Comment_082: l.587 LPJ? LPJ-wsl 1.0? LPJ-wsl2.0? All of them?

We changed all references to the current model to 'LPJ-wsl v2.0'.

Reviewer_2_Technical_Comment_083: l.593: again I would recommend clarifying "upper limit" and again I am not sure if this is correct, due to the oldest age-classes first principle for harvesting and deforestation (l. 233-239).

Per previous response, see below.

We removed the term 'upper limit' throughout. We added clarifying text as below.

"In some locations, it is possible that our wood harvest priority rules (harvest oldest age-class first) might lead to simulated stand ages that are younger than observed stand ages if other harvest rules were applied in practice, such as preferentially logging forests of intermediate age with a goal of preserving the oldest forests from harvest. We evaluated the age distribution by continent simulated by LPJ-wsl v2.0 to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data (SM Figure 11). The comparison shows that the simulated ages are consistently older than the GFAD dataset."

Reviewer_2_Technical_Comment_084: l.606 same here with the underestimation – given the oldest age-classes first principle I am not fully persuaded that it underestimation is granted.

Per previous response, see below.

We added text to clarify that we think our simulations represent the upper bound of age distributions, where 'bound' is meant to convey a range of values [lower, upper] of expectation. We added clarifying text as below.

"In some locations, it is possible that our wood harvest priority rules (harvest oldest age-class first) might lead to simulated stand ages that are younger than observed stand ages if other harvest rules were applied in practice, such as preferentially logging forests of intermediate age with a goal of preserving the oldest forests from harvest. We evaluated the age distribution by continent simulated by LPJ-wsl v2.0 to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data; we have added this comparison as a figure to the Supplement. The comparison shows that the simulated ages are consistently older than the GFAD dataset."

The GlobFIRM fire module underestimates burned area, see data for fire-model intercomparisons from FireMIP (Hanston et al. 2020); we have updated the Hanston et al. 2017 reference to the 2020 paper throughout. The FireMIP results confirms similar findings about GlobFIRM.

Reviewer_2_Technical_Comment_085: l.622 But isn't this model dependent? Maybe consider rephrasing, e.g. "suggesting that uncertainty in carbon residence time could potentially be reduced" or the like

Agreed, it can be model dependent. We added the clarifying text '..could potentially be reduced..' as suggested.

Reviewer_2_Technical_Comment_086: l.624-627: I do not agree that this is "the current state of knowledge", nor that "existing models that estimate the global land-use flux... do not include age dynamics". For the former and the latter please e.g. refer to findings of Yue et al. 2018, in addition, for the latter, the authors might have a look into other studies conducted with some of the models listed around l.55-57.

We respectfully disagree. Yue et al. 2018 report on a single grid cell (0.5 degree) idealized simulation and it does not represent consensus on the state of knowledge. We refer to global emissions from gross land use change being greater than net land use change based on Arneth et al. 2017.

Reviewer_2_Technical_Comment_087: l.631: consider adapting the subsection header since this subsection seems to be more about precipitation than demographic effects?

We added some text to the section in reference so that the section title reflects the content of the paragraphs therein.

Reviewer_2_Technical_Comment_088: l.662: is this only the case if using the unequal age-class setup?

No, NEP is greatest in the youngest age-class, regardless of the simulation setup.

Reviewer_2_Technical_Comment_089: l.664: LPJ? LPJ-wsl 1.0? Both?

We changed all references to the current model to 'LPJ-wsl v2.0'.

Reviewer_2_Technical_Comment_090: l.671: I assume this is the case in several of the models listed around l.55-57.

We aren't sure, one way or another, if this applies to other models. We know this does apply to LPJ-wsl v2.0.

Reviewer_2_Technical_Comment_091: l.675: consider adding "on the same machine" (if this is correct).

Not correct. LPJ-wsl v2.0 can be run distributed, in parallel, on multiple compute 'machines'.

Reviewer_2_Technical_Comment_092: l.680: The first 2-3 sentences seem to be incomplete?

The section was re-written and begins with the statements as below.

"In order of priority for improvement of the age-module: 1) improve age-class growth rates to align with observations, 2) improve representation of disturbances, 3) improve representation of early- and late-successional plant species and add vertical structural complexity such as understory/overstory canopy. Below, we provide suggestions and examples from the literature as how these improvements might be accomplished."

Reviewer_2_Technical_Comment_093: l.700: To my understanding JSBACH4 does not represent much vertical heterogeneity. You might want to have a look into e.g. ORCHIDEE-CAN (Naudts et al. 2015) or in individual based models (in addition to ED), e.g. LPJ-Guess (Bayer et al., 2017).

The phrasing 'much' is relative. Relative to LPJ-wsl v2.0, which has a single layer canopy, JSBACH4 provides a good example for future developments.

Reviewer_2_Technical_Comment_094: Table 1: LPJ-wsl v2.0?!

As above, we changed all references to the current model to 'LPJ-wsl v2.0'.

Reviewer_2_Technical_Comment_095: Table 2: * single-cell: included processes might not match the description in 2.3.4, l.318. * global: Initially I tried to associate each of the four questions with one of the simulations, due to the visual structuring of the rows of the table. Maybe merge cells and number questions?

We choose to leave as is. The questions are meant to be interpreted as 'objectives and questions', as in general questions we wished to answer using the global simulation data. There are other questions we address in the text for each simulation. The column was not meant to be a full enumeration of all research questions and associated findings we address within the main text.

Reviewer_2_Technical_Comment_096: Figure 1: please explain what you mean with "land use" in this context

In the context of LPJ-wsl v2.0, ‘Land Use’ refers to crop/pasture.

Reviewer_2_Technical_Comment_097: Figure 3: explain MI,MN & WI again.

We clarified as follows, “..for U.S. States of MI, MN, MN..”

Reviewer_2_Technical_Comment_098: Figure 5: consider increasing visibility by changing the y-axis of the first panel (max of -5/-6 kgCm-2).

We leave as is. We think the important content of the panel is sufficiently displayed while leaving room for the legend.

Reviewer_2_Technical_Comment_099: Figure 6: *consider adding simulation names (Sage and Snoage if I understood it correctly). * could you show the simulation starting from the spin-up, i.e. starting 1860? Is the difference between the simulations due to the spin-up or evolving in the course of the simulation?

The simulations have the same prescribed drivers (inputs). The differences between simulations are observed after spinup, yes.

Reviewer_2_Technical_Comment_100: Figure 7: * consider using (a) and (b) instead of left and right. * “LPJ-wsl simulations” consider adding simulation name from Table 2.

We kept ‘left’ and ‘right’.

Reviewer_2_Technical_Comment_101: Figure 9: Since SFireLU is more complete than SFire, consider using the solid line for this more complete set-up?

We left as is. We annotate each line in the plot with the associated simulation.

Reviewer_2_Technical_Comment_102: Figure 10: * consider using the same y-axis for better comparability (same SMFig1). *

We left as is.

Reviewer_2_Technical_Comment_103: l.988 model is can -> model can

Edited accordingly.

Reviewer_2_Technical_Comment_104: Figure 11: * l.993 “black is zero”? On the colour map it is yellow? * red (-0.3) and pink (0.7) are difficult to distinguish, maybe consider a change in the colour map.

Black is zero, black is not yellow, it is stated as such in the legend. We provide the actual datasets for individual inspection, so we decided to leave the color scheme as is.

Reviewer_2_Technical_Comment_105: Figure 12: consider labelling panels (a)-(d) instead of using top row, bottom row, top left and bottom left.

We prefer the top/bottom, left/right referencing. We don’t reference every panel in the plot in the text, otherwise this would be a good suggestion.

TRACK CHANGES: Revisions documented for the Main Text

Ecosystem age-class dynamics and distribution in the LPJ-wsl v2.0 global ecosystem model

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Abstract. Forest ecosystem processes follow classic responses with age, peaking production around canopy closure and declining thereafter. Although age dynamics might be more dominant in certain regions over others, demographic effects on net primary production (NPP) and heterotrophic respiration (Rh) are bound to exist. Yet, explicit representation of ecosystem demography is notably absent in many global ecosystem models. This is concerning because the global community relies on these models to regularly update our collective understanding of the global carbon cycle. This paper aims to present the technical developments of a computationally-efficient approach for representing age-class dynamics within a global ecosystem model, the LPJ-wsl v2.0 Dynamic Global Vegetation Model, and to determine if explicit representation of demography influenced ecosystem stocks and fluxes at global scales or at the level of a grid cell. The modeled age classes are initially created by simulated fire, and prescribed wood harvesting or abandonment of managed land, otherwise aging naturally until an additional disturbance is simulated or prescribed. In this paper, we show that the age-module can capture classic demographic patterns in stem density and tree height compared to inventory data, and that simulated patterns of ecosystem function follow classic responses with age. We also present a few scientific applications of the model to assess the modeled age-class distribution over time and to determine the demographic effect on ecosystem fluxes relative to climate. Simulations show that, between 1860 and 2016, zonal age distribution on Earth was driven predominately by fire, causing a 45-60 year difference in ages between older boreal (50N-90N) and younger tropical (23S-23N) ecosystems. Between simulation years 1860 and 2016, land-use change and land management were responsible for a decrease in zonal age by -6 years in boreal and by -21 years in both temperate (23N-50N) and tropical latitudes, with the anthropogenic effect on zonal age distribution increasing over time. A statistical model helped reduced LPJ-wsl v2.0 complexity by predicting per-gridcell annual NPP and Rh fluxes by three terms: precipitation, temperature and age class; at global scales, R^2 was between 0.95 and 0.98. As determined by the statistical model, the demographic effect on ecosystem function was often less than 0.10 kg C m^{-2} yr^{-1} but as high as 0.60 kg C m^{-2} yr^{-1} where the effect was greatest. In eastern forests of North America, the simulated demographic effect was of similar magnitude, or greater than, the effects of climate; simulated demographic effects were similarly important in large regions of every vegetated conti-

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nent. Simulated spatial datasets are provided for global ecosystem ages and the estimated coefficients for effects of precipitation, temperature and demography on ecosystem function. The discussion focuses on our finding of an increasing role of demography in the global carbon cycle, the effect of demography on relaxation times (resilience) following a disturbance event and its implications at global scales, and a finding of a 40 Pg C increase in biomass turnover when including age dynamics at global scales. Whereas time is the only mechanism that increases ecosystem age, any additional disturbance not explicitly modeled will decrease age. The LPJ-wsl v2.0 age-module represents another step forward towards understanding the role of demography in global ecosystems.

1 Introduction

Forest ecosystem production follows predictable patterns with time since disturbance. Classic forest age-production curves from Odum (1969) suggest that net ecosystem production (NEP) peaks around canopy closure, declining thereafter due to hydraulic limitations on gross primary production (Ryan et al. 2004, Drake et al. 2010, 2011) and increases in heterotrophic respiration from biomass turnover due stand-level declines in population density (Ptrezsch and Biber 2005, Stephenson et al. 2014). That younger forests are more productive than older forests has been long-standing knowledge in forestry, as evidenced by yield and growth tables dating back to the 18th Century that incorporated stand age into their calculations of lumber production (Pretzsch et al. 2008).

On global scales, forest age is a considerable factor in the global carbon cycle and comprises a large fraction of the total land carbon sink, which is estimated at 3.2 ± 0.8 Pg C yr^{-1} for years 2008-2017 (Le Quere et al. 2018). According to country-level forest inventories, net carbon uptake from post-disturbance tropical forest regrowth is 1.6 ± 0.5 Pg C yr^{-1} from 1990 to 2007 (Pan et al. 2011a). Although the timeframes for estimates of the total lank sink and the inventory-based regrowth flux do not perfectly overlap, the magnitude of the regrowth sink relative to the total land sink warrants that models take regrowth dynamics into account. A multi-model global regrowth analysis with demographically-enabled DGVMs, for which LPJ-wsl v2.0 contributed, estimated that post-disturbance regrowth comprised a large global regrowth sink of 0.3 to 1.1 Pg C yr^{-1} due to demography alone over years 1981-2010 (Pugh et al. 2019a). In the last decade, explicit model representation of forests as a function of time since disturbance (hereafter simply, 'ecosystem age') has been a grand challenge in an effort to quantify the demographic response of forests to changes in climate, atmospheric CO_2, , land-use change and landmangement (LUCLM) and fire (Friend et al. 2014, Kondo et al 2018, Pugh et al. 2019a). Much of the focus of these global modeling studies has been on the effect of natural and anthropogenic disturbances on the carbon dynamics in old-growth versus second-growth forests (Gitz and Ciais 2003, Shevliakova et al. 2009, Kondo et al 2018, Yue et al. 2018, Pugh et al. 2019a), but lack finer distinction of demographic effects at different ageclasses. Following a call to the science community to improve demographic representation in models (Fisher et al. 2015), there is now a growing list of global models that are capable of simulating global ecosystem demographics (Gitz and Ciais 2003, *Model*: OSCAR; Shevliakova et al. 2009, *Model*: LM3V; Haverd et al. 2014, *Model*: CABLE-POP; Lindeskog et al. 2013, *Model*: LPJ-GUESS; Yue et al. 2018, *Model*: ORCHIDEE MICT; Nabel et al. 2019, *Model*: JSBACH4), although more models need the capability

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to represent landscape heterogeneity in forest structure and function.

Much of the evidence for the relative importance and global distribution of large disturbances has come from either satellite retrievals of spectral indices indicating forest loss or burn scars on the land (Potter et al. 2003, Frolking et al. 2009, Pugh et al. 2019b), national forest inventory records of land-use change and forest management (Houghton 1999, FAO-FRA 2015, Williams et al. 2016), or from model-based studies (Goldewijck 2001, Arneth et al. 2017) that integrate information on historical land use (Goldewijck 2001, Hurtt et al. 2006). Other natural disturbances such as pest and pathogen outbreaks, flooding, ice storms, and volcanic eruptions are less widespread globally (Frolking et al. 2009) but are still influential drivers of landscape age-class dynamics (Dale et al. 2001, Turner 2010). In the coterminous United States, forest management is the predominant forest disturbance (1.4% of forested area converted to non-forest and then re-established annually), followed by fire (0.01-0.5% of forested area burned annually 1997-2008) (Williams et al. 2016). Although pest and pathogens, namely bark beetle infestations, affected a much larger area (up to 6% of total forested area in U.S.) than both logging and fire, their effects do not always cause immediate tree mortality. It is arguable whether fire and LUCLM are the two most important global drivers of ecosystem age (Pan et al. 2011a), but nevertheless these are the drivers applied in a model framework in this study, in a manner that moves modeling one step forward to assess global age-class dynamics.

The overall aims of this study are to present new model developments that simulate the time-evolution of age-class distributions in a global ecosystem model and to determine if explicit representation of demography in this model influenced ecosystem stocks and fluxes at global scales or at the level of a grid cell. Technical details are presented for a module representing age-class dynamics, driven by fire feedbacks, land abandonment and wood harvesting in the LPJ-wsl v2.0 Dynamic Global Vegetation Model (DGVM). Prior versions of LPJ-wsl v2.0 that included early developments of the land-use change module and the age-class module have already contributed to prior studies (Arneth et a. 2017, Kondo et al. 2018, Pugh et al. 2019a). Analyses are presented of model behavior, in terms of age-structure and age-functional patterns, the temporal evolution of age distributions and their causative drivers, and a statistical model of ecosystem production and respiration as a function of demography and climate.

2 Methods

2.1 LPJ-wsl v2.0 General Model Description

2.1.1 LPJ History

LPJ-wsl v2.0 has its legacy in the LPJ family of models, first developed by Sitch et al. (2003) in a Fortran coding environment [1]. In 2007, Bondeau et al. (2007) produced the LPJmL codebase, in C, which included the addition of 'managed lands'. The model known as LPJ-wsl v2.0 is based on LPJmL v3.0, but includes modifications to managed lands that now includes modeling gross land cover transitions, forest age cohorts, and also a modification that

1. LPJ and LPJmL History, https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml/history-1)

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include permafrost and wetland methane. Many developments were made in the publicly-available LPJmL4 (version 4.0; Schaphoff et al. 2018) that are not present in LPJ-wsl v2.0. The LPJ-wsl v2.0 model was branched off of LPJmL sometime around 2010 and continued to diverge. This research paper represents a large effort toward this end, and the LPJ-wsl v2.0 code is now freely and publicly available (https://github.com/benpoulter/LPJ-wsl_v2.0) under a GNU Affero General Public License version 3. LPJ-wsl v2.0, excluding the version number unless an explicit reference is being made to prior versions or to clarify the version number.

2.1.2 LPJ-wsl v2.0 Overview

LPJ-wsl v2.0 simulates soil hydrology and vegetation dynamics in 0.5° grid cells, wherein climate, atmospheric CO_2, and soil texture is prescribed from driver datasets (Figure 1). Vegetation is categorized into Plant Functional Types (PFT; Box 1996). Plant populations compete for light, space, and soil water, depending on demand; nutrient cycles are not considered in this model version. LPJ-wsl v2.0 is a 'big-leaf' ecosystem model, whereby leaf-level photosynthesis and respiration (Haxeltine and Prentice 1996, Farquhar et al. 1980) occur at daily time-steps, accounting for the photosynthetically active period (daytime), and are scaled to the stand-level using a mean-individual approximation, which assumes that important state variables (carbon stocks and fluxes) can be determined by using the average properties of a population. Plant populations are categorized using 10 PFTs in this study (phenology parameters and bioclimatic limits listed in SM Table 1); the same PFTs as in Sitch et al. (2003). Left unchanged are the PFT-specific bioclimatic limits, turnover rates, C:N tissue ratios, allometric ratios, and other parameters not explicitly commented on here, but as described in Sitch et al. (2003). Mortality occurs via reductions in population density if a PFT's annual carbon balance is less than zero or if fire occurs. The fire module and the representation of land-use change and land management are described in detail in *Section 2.2.2*, as these modules require a greater number of modifications for integration with age-classes.

2.2 Age-class Module

2.2.1 An age-based model of ecosystems – sub-grid cell dynamics

Age classes are represented as 'patches' within a grid cell (Figure 1). Every age class has the same climate, atmospheric CO_2, and soil texture, but the properties of the age class, such as available soil water and light availability, are determined by feedbacks from plant demand within an age class. Plant processes (competition, photosynthesis, respiration) are simulated at the level of the age class for each PFT within the age class.

The age-class module has a fixed number of age-classes that can be represented in a grid cell, but all age-classes are not always represented. Age-classes are classified into 12 age-classes in fixed age-width bins, defined as the *unequalbin* or the *10yr-equalbin* age-width setup (Table 1). Each age class contains *within* age class elements, which are simply a vector representation of areas for each age-unit in the age class. The within-ageclass elements are not independent and every within-ageclass element has the same state variables, including the same soil water and light. As such, we only simulate processes at the ageclass level, and the within-ageclass elements are a simple method for a 'smooth' transition between ageclass. In theory, we can simulate processes independently for each within-ageclass

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element, but this is not practical or necessary. The main benefit for using equal-bin or unequal-bin ageclasses is to independently simulate processes. The age widths of the age classes in the *10yr-equalbin* setup correspond to common age widths of classes used in forest inventories; for contrast, JSBACH4 uses a 15-year age width in their equal-bin ageclass setup. Most ageclasses in this setup are represented by a vector of 10 elements, wherein each element represents an aerial fraction for each age-unit (Table1). The *10yr-equal*bin age setup is used for all simulations including the global simulation, whereas the *unequalbin* setup is used for regional and single grid cell simulations; simulation details in next section. The use of equal or unequal age class setups is more than just for reporting purposes. Resources available to plants (space, light, soil water) differ between age classes but not within age classes, and we limit the model to represent a total of 12 ageclasses only. Also, there exists a greater range of forest ages at global scales and the equal age-class setup allows us to independently model resource dynamics for more of the terrestrial surface. If we had chosen the unequal-bin setup for global simulations, we would be independently modeling processes only for the youngest age classes and we would lose capacity to independently model processes at intermediate and older age classes. A study by Nabel et al. (2020), using the demographically-enabled JSBACH4 DGVM, found that unequal binning of age widths had lower errors than equal age width binning but the largest reduction in model-observation error was achieved by simply adding more ageclasses at younger ages, regardless of the binning strategy employed.

Age classes are only created by disturbance and we only model the following disturbances: fire, wood harvest, or land abandonment, which initialize a new youngest age class. The fraction of the age class that burns gets its age 'reset' to the youngest age class, 1-10 yr. The same process occurs for the fractional area that undergoes wood harvest or when managed land is abandoned and allowed to regrow – the fractional area undergoing an age-transition is reclassified as a 1-10 yr age class. This process allows the model to accurately track the carbon stocks, fluxes and feedbacks associated with these state variables. For example, if a fire burns 50% of an age class, then 50% might have bare ground and 50% will have vegetation at pre-burn levels. If the probability of another fire is dependent on live vegetation, then feedbacks will result in a lower chance of fire on the bare-ground fraction versus the fully-vegetated fraction that was not previously burned.

The most novel advancement in this study is a new method of age-class transition modeling, which we call 'vector-tracking of fractional transitions' (VTFT), which improves the computational efficiency of modeling age classes in global models; this is a similar approach independently conceived by Nabel et al. (2019). The method is a transparent and simple solution to the problem of dilution, which manifests as an advective process when state variables, such as carbon stocks or tree density, are made to merge by area-weighted averaging. The concept of merging two unique age classes on the basis of similarity is a computational solution to constrain the number of simulated age classes in accordance with computer resources, but can be considered ecologically unrealistic. For example, along what axis of similarity is an age class considered to be most similar to another age class – in terms of PFT composition, biomass in plant organs, plant height, or stem density? Existing age class models (Medvigy et al. 2009, *Model*: ED2; Lawrence et al. 2019, *Model*: CLMv5.0; Yu et al. 2018, *Model*: ORCHIDEE-MICT) employ merging rules (although some do not – Lindeskog et al. 2013, *Model*: LPJ-GUESS) with varying thresholds to ensure that age clas-

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ses are only merged if the difference among one state variable (biomass, tree height) is less than a fixed threshold. We also merge age classes, but we do not employ merging rules along arbitrary axes of similarity. We fix the number of age classes *a priori*, similar to LPJ-GUESS in that there is a maximum number of age classes. Instead of forced merging to reduce computational burden (as in ED2), a fraction of the age class always transitions to an older state, and a fractional area can transition and merge with the next oldest age class. By design, VTFT allows age classes to advance in a natural progression from young to old and ensures that age-class transitions always occur between the most similar age classes along multiple state variables.

The theoretical description of the VTFT approach is described as following in matrix notation. VTFT describes a matrix of size (w := *agewidths per ageclass*, n := ageclasses), where the elements $f_{i,j}$ are the within-ageclass fractional areas of the grid cell:

$$\mathbf{F} = \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,n} \\ f_{2,1} & f_{2,2} & \cdots & f_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{w,1} & f_{w,2} & \cdots & f_{w,n} \end{bmatrix} = \left(f_{i,j} \in \mathbb{R}^{wxn}\right) \quad (1)$$

It is important to note here that within-ageclass fractional areas ($f_{i,j}$) are only used during age-class transitions – this is a key point. For almost all calculations in LPJ, processes operate on the total fractional area for each age class,

$$\mathrm{F_{total}} = \sum_{j=1}^{n}\sum_{i=1}^{w} f_{i,j}$$

$$\mathrm{F\_total}_j = \sum_{i=1}^{w} f_{i,j} \quad (2)$$

, where F_total is the sum of fractional areas for all grid cell age classes, defined as the sum of fractional areas for over age classes (n) and age widths (w). $\mathrm{F\_total}_j$ is the column sum of **F** for a given age-class (j); the calculation can be vectorized for efficiency by computing the dot product between an 'all-ones' row vector of length (w) and **F**. In practice, when LPJ-wsl v2.0 simulates physical processes on an arbitrary carbon pool (C), for example, the calculations are computed on a per-mass basis, which then requires conversion to a per-area basis by multiplying the total carbon mass in an age class by the representative total fractional area:

$$\mathrm{C_j}[\mathrm{kg\ m^{-2}}] = \mathrm{C_j}[\mathrm{kg}] \times \mathrm{F\_total_j} \quad (3)$$

, where C_j [*units* := kg or km^{-2}] is the total carbon for a given age-class (j). Again, the calculation can be computed via the Hadamard (element-wise) product, taking a vector ($\vec{C}$), where elements are the carbon pool totals for every age class and multiplying by vector F_total, with elements of the total fractional areas in each age class. In effect, all simulated processes in LPJ-wsl v2.0 act on an area-basis, based on the column sums of **F**.

In every year of simulation, an age-class transition always occurs, and this procedure is defined as an operation that increments the positions of the elements as,

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$$\mathbf{F}^{(t+1)} := \begin{bmatrix} f_{1,1}^{(t+1)} \stackrel{\text{def}}{=} f_{new}^{(t+1)} & f_{1,2}^{(t+1)} \stackrel{\text{def}}{=} f_{w,1}^{(t)} & \cdots & f_{1,n}^{(t+1)} \stackrel{\text{def}}{=} f_{w,n-1}^{(t)} \\ f_{2,1}^{(t+1)} \stackrel{\text{def}}{=} f_{1,1}^{(t)} & f_{2,2}^{(t+1)} \stackrel{\text{def}}{=} f_{1,2}^{(t)} & \cdots & f_{2,n}^{(t+1)} \stackrel{\text{def}}{=} f_{1,n}^{(t)} \\ \vdots & \vdots & \ddots & \vdots \\ f_{w,1}^{(t+1)} \stackrel{\text{def}}{=} f_{w-1,1}^{(t)} & f_{w,2}^{(t+1)} \stackrel{\text{def}}{=} f_{w-1,2}^{(t)} & \cdots & f_{w,n}^{(t+1)} \stackrel{\text{def}}{=} f_{w,n}^{(t)} + f_{w-1,n}^{(t)} \end{bmatrix} \quad (4)$$

, where the superscripts are the time indices for the current timestep (t+1) and the previous timestep (t), subscripts are the matrix indices, $f_{new}^{(t+1)}$ is the fractional area of a newly created stand (by definition, it is the youngest age-class fraction), and $f_{w,n}$ is the oldest fractional age of the grid cell, which is incremented by an amount equal to fractional area ($f_{w-1,n}^{(t)}$). Of special importance is the bottom row of the **F** matrix, $F_{w,1 \leq j \leq n}$, which are the fractional areas of each age class transitioning to the next oldest age class. The transitioning fractions (F_{w*}) become the incoming fractions in the next-oldest age class. Using an arbitrary carbon pool (C) as an example, the carbon pool for the next timestep (t+1) would be calculated via an area-weighted average between the carbon remaining in the age class and the carbon in the transitioning fraction,

$$C_j^{(t+1)} = \frac{\left(C_j^{(t)} \times F'\_total_j^{(t)}\right) + \left(C_{j-1}^{(t)} \times f_{w,j-1}^{(t)}\right)}{F'\_total_j^{(t)} + f_{w,j-1}^{(t)}} \quad (5)$$

, where F'_total_j is the total fractional area of age-class (j) that remains in the age-class, $f_{w,j-1}^{(t)}$ is the transitioning or 'incoming' fraction from the younger age class, and $C_{j-1}^{(t)}$ is the carbon pool (on area-basis, kg m^{-2}) in the younger age class, calculated at the end of the previous timestep. Equation 5 effectively converts the units of the carbon pools from an area-basis (km m^{-2}) to a total mass (kg), taking the sum of the carbon remaining and transitioning into the age class, and 'redistributes' the carbon mass by the new fractional area; during age-class transitions, these area-weighted averages are used to conserve mass across all state variables. In theory, VTFT minimizes the redistribution (or 'dilution') of mass across a larger area if the incoming fractional area is much smaller than the fractional area of the existing age class.

In a plain-language summary of the matrix representation, VTFT ensures that a vector of fractional areas is associated with every age-class (n), of length (w), and where 'w' is equal to the age width of the age class, with elements (f) that are the fractional areas contributing to the total fractional area of the age class (F_total). When a young age-class (a_1) is first created, VTFT vectors are initialized to zero and the first element (f_1) is set to the *incoming* fractional area. The following is a description for within-class and between-class transitions. *Within-class Fractional Transitions*: For every simulation year, the position of each element (f_x) in the VTFT vector is incremented by the representative time of each element (x), which is simply 1. No changes occur to the state variables of the age class during within-class transitions. *Between-class Fractional Transitions*: Upon incrementing the position of each element in the VTFT vector, if the value at f_w is non-zero then the corresponding fractional area f_w, defined as the outgoing fraction, is used in an area-weighted average between the state variables of $a_1 f_w$ and the next oldest age-class a_2 F_total. Upon incrementing the element position, if all elements in the VTFT vector of the preceding age-class are zeros then the age class is simply deleted from computational memory.

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Two hypothetical scenarios are provided in Figure 2 that demonstrate age-class transitions using the VTFT procedure when there is a young age class created, and when there are fractional age-class transitions between age classes. With VTFT, any number of age classes and age widths can be modeled, but it is demonstrated in this study that the age widths employed in this study are sufficient to minimize the dilution of state variables when area-weighted averaging is used to merge fractional age classes while also simulating stand-age patterns in state variables of carbon stocks, stem density and fluxes.

2.2.2 Integration with fire and land-use change and land management (LUCLM) modules

Fire – The fractional area burned initiates the creation of a youngest age class, or it gets merged with a youngest age class if one exists already. Fire simulation is based on the semi-empirical Glob-FIRM model by Thonicke et al. (2001), with implementation details described in Sitch et al (2003). In short, fire is dependent on the length of the fire season, calculated as the number of dry days in a year above a threshold and a minimum fuel load, defined only as the mass of carbon in litter. When a fire occurs, PFT-specific fire resistances determine the fraction of the PFT population that gets burned. The biomass of burned PFTs, along with the aboveground litter in the age class, gets calculated as an immediate flux to the atmosphere. The fraction of the PFT population that does not burn maintains state variables (e.g., tree height, carbon in leaf and wood) at previous values; it is possible to have so called 'survivor' trees on the youngest age class that then skews the age-height distribution of the age class.

LUCLM – Age classes get created when managed land (i.e., crop/pasture) is abandoned and allowed to regrow into secondary forests, or when wood harvest occurs on forested lands and causes deforestation. In both cases, the fractional area abandoned/logged initiates the creation of a youngest age class, or it gets merged with a youngest age class if one exists already. To improve accounting of primary forests, defined here as natural land without a history of LUCLM, and second-growth forests, defined as natural land with a history of LUCLM; transitions between these classes are unidirectional from primary to secondary. In the LUCLM module, gross transitions between land uses are simulated (Pongratz et al. 2014, Stocker et al. 2014), such that if the fraction of abandoned land equals the fraction of land deforested in the same year (net zero land-use change), then the fluxes from the gross transitions are tracked independently and give an overall more accurate accounting (and higher magnitude) of emissions from LUC than if we only tracked net transitions (Arneth et al. 2017).

General rules distinguishing primary and secondary stands within the age class context stem from the Land Use Harmonization dataset version 2 (LUHv2; Hurtt et al. 2020), but with the following modifications so that the LUHv2 data can be used in LPJ-wsl v2.0: (1a) the primary grid cell fraction only decreases in size and never gets mixed with existing secondary forests or with abandoned managed land. Only fire creates young age classes on primary lands. (2a) secondary grid cell fractions can be mixed with other secondary forest fractions, recently abandoned land, fractions with wood harvest, and recently burned area. General priority rules for deforestation and wood harvest: (1b) For simplicity, deforestation (i.e., land-use change) always occurs in the ranking of oldest to youngest age class, proceeding to deforest each age class until the prescribed fractional area of deforestation is met. This rule

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will always result in greater land-to-atmosphere fluxes than if rules were employed that allowed younger age classes to be preferentially deforested. (2b) wood harvest (i.e., biomass harvest) also occurs in the ranking of oldest to youngest age class until two conditions are met. Timber harvest occurs on each age class until a prescribed harvest mass or harvest area is met.

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Treatment of immediate emissions and residues: Deforestation results in 100% of heartwood biomass and 50% of sapwood biomass being stored for delay emission in product pools; root biomass is entirely part of belowground litter pools, while 100% leaf and 50% of sapwood biomass becomes part of aboveground litter pools. Grid cell fractions that underwent land-use change were not mixed with existing managed lands or secondary fractions until all land-use transitions had occurred. This avoids a computational sequence that results in a lower flux if deforestation and abandonment occur in the same year. For wood harvest, 100% of leaf biomass and 40% of the sapwood and heartwood enters the aboveground litter pools, and 100% of root biomass the belowground litter pools; 60% of sapwood and heartwood are assumed to go into a product pool for delayed emission.

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Timber from deforestation and harvest in product pools for delayed emission (Earles et al. 2012): For deforestation, 60% of exported wood (i.e., not in litter) goes into a 2-yr product pool and 40% goes into a 25-yr product pool, following the 40:60 efficiency assumption from McGuire et al. (2001). For wood harvest, the model uses space-time explicit data on harvest fractions going into roundwood, fuelwood and biofuel product pools. We use three product pools and assume that 100% of the fuelwood and biofuel fraction goes into the 1-year product pool (emitted in the same year of wood harvest), 50% of the roundwood fraction goes into the 10-year product pool (emitted at rate 10% per year) and the remaining 50% of the roundwood fraction goes into the 100-year product pool (emitted at rate 1% per year).

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2.3 Experimental Design and Analysis

2.3.1 Model inputs

Inputs to the model are gridded soil texture (sand, silt, clay fractions) from the USDA Harmonized World Soils Dataset v1.2 (Nachtergaele et al. 2008), annually-varying global-mean [CO_2] (time series available in supplement), and monthly-varying air temperature, precipitation, precipitation frequency, and radiation from the Climate Research Unit (CRU, version TS3.26) data for 1901-2016. Land use, land-use change, and wood harvest were prescribed annually based on the Land Use Harmonization dataset version 2 (LUHv2; Hurtt et al. 2020), which is used as forcing land-use for the 6th Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016). The dataset includes fractional area of bi-directional (gross) land-use transitions between forested and managed lands, as well as the total biomass of wood harvest on a specified fractional area logged. In LPJ-wsl v2.0, managed lands (i.e., crop/pasture) are treated as grasslands with no irrigation, no fire, and tree PFTs were not allowed to establish. Model representation of land management is an oversimplification to focus on effects of wood harvest.

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2.3.2 Qualitative evaluation of simulated stand structure against U.S. Forest Inventory Analysis (FIA) data

U.S. Forest Inventory and Analysis (FIA) – The FIA dataset is freely available at the FIA DataMart web portal (FI-ADB version 1.6.0.0.2), accessed 2 February 2016. The FIA plot level data are composed of 4 circular sub-plot sample areas (168 m^2), wherein attributes of all trees with Diameter at Breast Height (DBH) ≥ 5.0 inches (12.7 cm) diameter are recorded. We extracted variables that capture two main axes of structural change as a function of forest age: stem density and tree height. Spatial coordinates of sample plots are 'fuzzed' with imposed error for privacy reasons (FIA User Guide v 6.02; O'Connell et al. 2015). For purposes of this analysis, plot data were aggregated to the spatial scale of U.S. Forest Service *Divisions* (SM Figure 2; USFS Divisions are delineated by regional-scale precipitation levels and patterns as well as temperature) minimizing co-location concerns between model-observation comparisons. We filtered the FIA data based on the following criteria. We only included plots that used the national standard plot design (DESIGNCD=1) and were located on forested land (COND_STATUS=1) with no history of major disturbance, stocking, or logging (DSTRBCD=0, TRTCD1=0). We also only included plots that had both sub-plot samples of live tree (STATUSCD=1) stem density and also circular micro-plot (13.5 m^2) stem density samples of seedling/sapling (defined as trees 1 to 5 inches [2.54 to 12.7 cm] in diameter), and where the sub-plot sampling design was the national standard (Tree Table SUBP = [1,4]); LPJ-wsl v2.0 implicitly includes sapling and adult trees in estimates of tree height and stem density. We assumed that the filtered plots were representative of the true density and distribution of tree species for the general vicinity of the plots and of the USFS Division. Although these requirements for selecting FIA plots reduce the total amount of data, we aimed to make evaluations in a fair manner, in both spatial scale and meaning.

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2.3.3 Examining age dynamics: regional simulation for assessing changes in stand structure and ecosystem function

The objectives of the regional simulations were to evaluate demographic patterns of stand structure and function when simulating age classes using different age-width binning. Two ideal simulations were conducted at a regional scale to sample simulated annual stem density, average tree height, and NEP. The first simulation used the *unequal-bin* age-width setup, $\mathbf{S}_{\mathbf{unequalbin}}$, and another used the *10-yr-equalbin* age-width setup, $\mathbf{S}_{\mathbf{10yrbin}}$ (Table 2). For both simulations, Fire and LUCLM were not simulated. Instead, 5% of the fractional area of age-classes > 25 years were cleared of biomass annually; the fractional area cleared was re-classified and merged with the youngest age class. The intent of the setup was to ensure that each grid cell maintained fractional area in every age class for each year of the simulation and avoided situations in which age classes were only present in 'bad years', or when growing conditions were poor. Both simulations were conducted with a 1000-yr 'spinup' using fixed CO_2 (287 ppm, 'pre-industrial' values) and climate randomly sampled from 1901-1920 to ensure that age distributions were developed and state variables were in dynamic equilibrium (i.e., no trend). A transient simulation then used time-varying CO_2 and climate, as prescribed by model inputs. Stand structure data were analyzed for 1980-2016.

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The idealized simulations were performed for the mixed deciduous and evergreen forests of Michigan, Minnesota and Wisconsin, U.S.A (bounding box defined by left: 97.00º W; right: 82.50º W, top: 49.50º N, bottom: 42.00º W). These forests are of moderate temperate climates, with total annual rainfall 815.0 mm/yr (average over 1980-2016, based on CRU TS3.26) with monthly minimum 21.0 mm/mo and maximums of 148.5 mm/mo. Mean annual temperature (1980-2016, CRU TS3.26) was 5.98º C with monthly minimum of –11.45º C and maximum 20.98º C.

Data were pooled for the region over the time period and by age class. Data were plotted in box plots to show median value, interquartile range and outliers. No attempt was made to de-trend data because there was enough between age class variation to evaluate general demographic patterns visually.

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2.3.4 Examining resilience: idealized simulation of a single event of deforestation, abandonment, regrowth

The objective of the idealized simulation was to evaluate the effect of age classes on relaxation times following a single deforestation, abandonment and regrowth event within a single grid cell (Table 2). The relaxation time is defined as the time required for a variable to recover to previous state and is a direct measure of ecosystem resilience (*sensu* Pimm 1984). Two simulations were conducted, the first simulation used the *10-yr-equalbin* age-width setup, $\mathbf{S_{age\_event}}$, and another did not simulate age classes, $\mathbf{S_{noage\_event}}$ (Table 2). Both simulations were conducted with a 1000-yr 'spinup' using fixed CO_2 (287 ppm, pre-industrial value) and climate randomly sampled from 1901-1920 to ensure that state variables were in dynamic equilibrium. A transient simulation then used time-varying CO_2 and climate, as prescribed by model inputs. Fire and LUCLM were not simulated. Instead, 25% of the fractional area was deforested in year 1910 of the simulation and classified as managed land. Treatment of deforestation byproducts (i.e., carbon in dead wood left on-site) were the same in both simulations. In the following year (1911), the managed land fraction was abandoned and allowed to regrow. The following state variables were plotted over time and visually evaluated: Net Biome Production (NBP, defined as NBP = NEP – LUC_flux), NEP, NPP, Rh, carbon in biomass.

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The idealized simulations were performed for a single grid cell in a mixed broadleaf and evergreen needleleaf forest in British Columbia, CAN (121.25º W 57.25º N). The grid cell is a boreal climate with total annual rainfall 473.7 mm/yr (average over 1980-2016, based on CRU TS3.26) with monthly minimum 9.11 mm/mo and maximums of 105.8 mm/mo. Mean annual temperature (1980-2016, CRU TS3.26) was 0.59º C with monthly minimum of –16.9º C and maximum 14.7º C.

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2.3.5 Global simulation objectives and setup

There were three main objectives for global simulations. The first objective was to evaluate the contribution of age class information to global stocks and fluxes. Here, a simulation with age classes ($\mathbf{S_{age}}$) was compared to a simulation without age class representation ($\mathbf{S_{noage}}$) (Table 2). The second objective was to determine the relative influence of fire and LUCLM on the spatial and temporal distribution of ecosystem ages. For this objective, a Fire-only simulation ($\mathbf{S_{Fire}}$) only had age classes created by fire, whereas a LUCLM-only simulation ($\mathbf{S_{LU}}$) had age classes only created by abandonment of managed land or by wood harvest (Table 2). A simulation with both Fire and LUCLM ($\mathbf{S_{FireLU}}$) was used as the baseline for comparison against $\mathbf{S_{Fire}}$ and $\mathbf{S_{LU}}$. The third and fourth objectives used data from $\mathbf{S_{age}}$ ($\mathbf{S_{age}} = \mathbf{S_{FireLU}}$) to determine where the effect of demography was greatest and to identify the relative influence of demography versus climate on simulated fluxes (NEP, NPP, and Rh).

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For all global simulations, a spinup simulation was run for 1000 years using randomly sampled climate conditions from 1901-1920 and atmospheric CO_2 fixed at pre-industrial levels (287 ppm) and no land use or wood harvest; spinup ensured that age distributions and state variables were in dynamic equilibrium (i.e., no trend). For simulations with land use, a second 'land-use-spinup' procedure was run for 398 years to initialize land use fractions of crop/pasture to year 1860, resampling climate and fixing CO_2 as in the first spinup. After spinup procedures, climate and CO_2 were allowed to vary until simulation year 2016; in $\mathbf{S_{LU}}$ and $\mathbf{S_{FireLU}}$, land-use change and wood harvest varied annually as prescribed by the LUHv2 dataset.

In the first objective (as above), global values for stocks and fluxes include both natural and managed lands. These global estimates conform to typical presentation of global values (Le Quéré et al. 2018), in Petagrams (10^{15}) of carbon. Comparisons are made among simulation types and to values from the literature.

For the second objective, a time series of zonal mean ecosystem ages were analyzed to determine the relative importance of $\mathbf{S_{Fire}}$ and $\mathbf{S_{LU}}$ on the observed distributions in $\mathbf{S_{FireLU}}$. The first assessment was made by visual inspection of zonally-averaged time-series (i.e., Hovmöller plots) for the entire period of transient simulation, years 1860-2016. In addition, for each of $\mathbf{S_{Fire}}$ and $\mathbf{S_{FireLU}}$, a simple linear regression model (age = $ß_0 + ß_1$*year, setting 1860 as the reference year and defined as 1) was applied to identify trends in ecosystem age by the following zonal bands: boreal (50˚ N to 90˚ N), temperate (23˚ N to 50˚ N), and tropics (23˚ S to 23˚ N). Trends in age distributions due to LUCLM are not prescribed by inputs per se; instead, the age module is a necessary model structure that allows full realization of the effect of forcing data on age distributions. Trends in age distribution due to Fire, which is a simulated process as opposed to prescribed, result from climate and fuel load feedbacks on fire simulation.

2.3.6 Statistical model to assess relative importance of demography and climate

For the third objective of global simulations – to reduce dimensionality of the data and to assess the relative influence of demography and climate on simulated fluxes – annual flux data from $\mathbf{S_{age}}$ (Table 2) were analyzed from 2000-2016 using generalized linear regression model,

$$flux_{i,yr} = B1_i \times \text{total\_precipitation}_{i,yr} + B2_i \times \text{mean\_temperature}_{i,yr} + B3_{i,ageclass} \times ageclass_{i,yr} \quad (6)$$

, where *flux* was one of {NEP, NPP, Rh} in kg C m^{-2} yr^{-1}, precipitation (mm) and temperature (Celsius) data from CRU TS3.26, and age-class was categorical, defined by the age-class code (Table 1), and the beta coefficients (*B*) for subscripts of grid cells (*i*), years (*yr*) and age class. The beta coefficients are therefore unique to every grid cell, and the betas for age classes are estimated separately for each age class within the grid cell ($B3_{i,age}$). An initial test of the model attempted to estimate globally-consistent predictor effects, but the model was found to be a poor fit (*not shown*) and it was assumed that there was too much variation among grid cells to detect globally-consistent effects. Instead of adding additional gridded fields of predictor variables to account for gridcell-level variation, the same statistical model was applied and analyzed per-gridcell. This allowed coefficients of precipitation, temperature and

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age-class to vary by grid cell, in essence, reducing the effect of variation in PFT composition, soil texture and hydrology that might otherwise reduce predictive power.

In all grid cell analyses, the intercept term was intentionally omitted from the data model by adding a '-1' term to the data model. The age-class term in the statistical model ($B3_{i,age}$), as a categorical variable, effectively takes the place of the intercept term anyhow, so the outcome is that estimates are for the absolute effect of each age class on the predicted flux as opposed to estimates that were relative to the first age class; this had no impact on estimated coefficients but it did simplify analyses. In grid cells where only a single age class was present, the statistical model was defined as ($flux_{i,yr} = B1_i$ total_precipitation$_{i,yr}$ + $B2_i$ mean_temperature$_{i,yr}$ + $B3_i$), leaving the intercept term, in this case – $B3_i$, to be estimated from the data and then re-classifying the intercept term by the age-class code for the grid cell.

The degrees of freedom (d.f.) of a model for a grid cell with a single age-class was d.f.=14, based on 17 annual data points to estimate coefficients of three predictors. The degrees of freedom for a grid cell that had a maximum of 12 age-classes was d.f.=190, based on 204 annual data points to estimate coefficients for 14 predictors. Because the analysis produced statistical results for every grid cell, the degrees of freedom are not presented elsewhere. Coefficients were only analyzed or mapped when significant at p=0.05.

3 Results

3.1 Model Stand Structure – comparison against inventory data

FIA data were not equally available for every age class, nor for every Division (Figure SM2), but there were enough inventory data across 8 Divisions, spanning subtropical to temperate steppe climates, to qualitatively suggest that LPJ-wsl v2.0 does capture the expected patterns of tree density and height per age in the different climates evaluated. There was a tendency to overestimate stem density in younger age classes and systematically underestimate tree heights among age classes (e.g., Figure SM3, Figure SM5), for which the greater number of small individuals could cause the average tree heights to be dampened. However, LPJ-wsl v2.0 is a big-leaf, single-canopy model and it does not represent multiple pft cohorts in an age class, or more simply, it does not represent vertical heterogeneity. As such, and under the current model architecture and associated assumptions, the cause of the mis-match is unclear. Even still, the more general pattern of modeled stem density and tree height tended to track FIA data, with stem density being maximal in the younger age classes and declining thereafter, whereas tree height patterns increased more linearly before stabilizing (Figure SM6 to SM9).

FIA data had greater variability among age classes, regardless of Division. FIA data are not aggregated by PFT, instead they are species-level data. Changes in species composition over time do occur and it can add to the observed variability among age classes in tree density and tree height. LPJ-wsl v2.0 includes a limited set of PFTs, which most likely limits the model's capacity to represent similar levels of variation in tree density and tree height. It is beyond the scope of this study to disentangle these patterns further, but greater agreement between observed and

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simulated patterns of forest structure might be acheived by including additional plant functional types that are representative of tree species for a given Division.

3.2 Model Age Dynamics

3.2.1 Dynamics of stand structure and function – regional simulations

Forest structural characteristics of stem density, height, and NEP followed the expected patterns with age with a few exceptions. In $\mathbf{S_{unequalbin}}$ (Table 2), stem density increased from near zero to maximum in the 21-25 yr age-class, before declining non-linearly (Figure 3). By contrast, the gradual increase in stem density in the first age class in $\mathbf{S_{10\text{-}yrbin}}$ (Table 1) was not readily apparent because this process, which is evident in $\mathbf{S_{unequalbin}}$, occurs entirely within the youngest 1-10 yr age-class in $\mathbf{S_{10\text{-}yrbin}}$. Both simulation setups approach the same stem densities after age ~25; prior differences are due to binning of age widths.

For average tree height in $\mathbf{S_{unequalbin}}$, there were large tree heights in the youngest age class, which results from so-called ‘survivor’ trees (Figure 3). Not all trees are killed-off when a disturbance occurs in LPJ. Although the age class is ‘reset’ to the youngest age class, the survivor trees skew the height distribution until the density of establishing saplings subsequently increases and brings down the average tree height to smaller values. This pattern is more akin to what occurs during natural fires or selective harvesting, which can reduce the overall age but might not result in a complete removal of all trees. By contrast, the skewed age-height pattern is not apparent in $\mathbf{S_{10\text{-}yrbin}}$ (Figure 3) only because the same process is effectively hidden. Both simulation types approach the same average tree heights after age ~25 (Figure 3).

NEP peaked at age-class 5-6 in $\mathbf{S_{unequalbin}}$, before declining non-linearly to the lowest average value in the oldest age class (Figure 3). Although the unimodal peak was not apparent in $\mathbf{S_{10\text{-}yrbin}}$, the maximum NEP occurred in the youngest age class and also declined non-linearly thereafter (Figure 3). The decline in NEP after a maximum at 5-6 years was driven mainly by an increase in Rh due to increases in turnover rather than a larger decline in NPP (Figure 4). The peak in NEP did not coincide with maximum tree density at ~20 years. Instead, model dynamics suggest that the total foliar projective cover of tree canopies reaches near maximum (80-95% cover, *not shown*) at 5-6 years, thereafter plant competition reduces NPP while biomass turnover increases, which together cause the apparent decline in NEP. The time period of canopy closure, at 5-6 years, in LPJ-wsl v2.0 is probably too early, in part due to advanced regeneration (saplings establish at 1.5 m height) and constant establishment rates. The age-class module qualitatively demonstrates NEP-age relationships consistent with field-based evidence (Ryan et al. 2004, Turner 2010).

Lastly, an emergent pattern was found in the declining portion of the NEP-age curve and approximately follows the functional form $NEPmax*0.70^{age\text{-}agemax}$, where *NEPmax* is the maximum NEP flux at the initial point of decline, *age* is the age of the patch, and *agemax* is the age of the patch where NEP is maximized. Thus, the non-linear decline in NEP is approximately 30% with increasing age. The functional equation holds between year 5-6 to year 25, after

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which NEP decreases only by 20% with increasing age and the functional form becomes $NEP_{25yr}*0.80^{age-25}$, where NEP_{25yr} is the NEP at year 25. The functional form of the decline in NEP is consistent among climate regions when simulated data is analyzed separately for all U.S. States (*not shown*). **The binning strategy is likely not a determinant of this pattern between NEP and stand age, which is evident in Figure 3 for both age-class setups. In this regard, we care less about the binning strategy and more that the emergent pattern is reflective of simulated model dynamics. This emergent pattern could lend itself to observational constraints if similar emergent patterns can be derived from forest inventory data in the future.**

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3.2.2 Time-series evolution of a deforestation, abandonment and regrow event

A single event of deforestation, abandonment and subsequent forest regrowth caused long-lasting effects and unrealistic model behavior when omitting age-class dynamics. In the simulation without age classes, $\mathbf{S}_{noage\_event}$ (Table 2), NEP takes ~30 years to recover to values prior the event, whereas the age-class simulation, $\mathbf{S}_{age\_event}$, takes only 5-6 years to recover (Figure 5) – a 5-fold change in relaxation times. The quick recovery of NEP in $\mathbf{S}_{age\_event}$ is due partly to the fact that the fraction of the grid cell (75%) that was *not* deforested maintained its state variables (carbon stocks in vegetation, soil, litter) unchanged from its prior state, which buffered NEP and dampened the effect of the smaller fraction (25% of grid cell) that was deforested. Age-class dynamics also contributed an elevated NEP (Figure 5) that quickens the recovery at the grid cell level. In $\mathbf{S}_{age\_event}$, there is an elevated NEP in the secondary stand that is sustained for more than 30 years following the event.

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In $\mathbf{S}_{noage\_event}$, vegetation dynamics cause turnover to increase and causes an elevated Rh that is consistently higher than NPP for 30 years after the event. This pattern is striking because NPP recovers quicker than in $\mathbf{S}_{age\_event}$ and maintains an elevated value for ~30 years. Following a disturbance event in LPJ, stem density and foliar projective cover is reduced but the state variables (carbon in plant organ pools of leaf, stem, root) maintain prior values; this is the reason NPP recovers quickly in the standard-no-age simulation. As stand density increases again, canopy closure initiates competitive dynamics that result in mortality of individuals of the plant population that are generally larger than if the stand had progressed from small to large individuals (as in $\mathbf{S}_{age\_event}$). The VTFT age-class module also uses the mean-individual approximation, but these unrealistic model dynamics are effectively dampened because stand dynamics are always allowed to occur in natural progression and the relatively small age widths (10-years) ensure that stand age dynamics (NEP-age trajectories in Figures 3 and 4) most evident in the first 50 years are discretely modeled.

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3.3 Global Stocks, Fluxes, and Age Distribution

3.3.1 Stocks and fluxes – $\mathbf{S}_{noage}$ versus $\mathbf{S}_{FireLU}$ and convergence in global NEP.

Carbon stocks in biomass are lower in $\mathbf{S}_{age}$ than in $\mathbf{S}_{noage}$ by ~40 Pg C globally (Figure 6). Lower global biomass in $\mathbf{S}_{age}$ can be explained by feedbacks from LUC and Fire that create younger age classes that have lower overall biomass than in older stands. In addition, age dynamics cause turnover to increase (as in Figures 3 and 4), causing soil carbon to be greater by ~35 Pg C and litter carbon to be greater by 5 Pg C. Taken together, age-class dynamics cause

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40 Pg C to be re-allocated from the living biomass pool to the soil-detrital pool, which compounds to alter the magnitude of fluxes from heterotrophic respiration. Demographic changes in turnover, such as these, are already known to be a large source of uncertainty among projections by global ecosystem models (Friend et al. 2014). What these numbers emphasize, however, is that uncertainty among models could be reduced by explicitly modeling age dynamics.

Net Ecosystem Exchange (NEE; positive fluxes to atmosphere) is only marginally different between $\mathbf{S}_{\mathbf{noage}}$ and $\mathbf{S}_{\mathbf{age}}$ simulations (mean difference of 0.25 Pg C yr^{-1} over 2000-2010). Compensatory fluxes in Fire and Rh explain the small difference in NEE at global scales. Fire fluxes in $\mathbf{S}_{\mathbf{age}}$ are lower by 0.92 Pg C yr^{-1} in the 2000s than in the $\mathbf{S}_{\mathbf{noage}}$, but fluxes from Rh are greater in $\mathbf{S}_{\mathbf{age}}$ by 1.61 Pg C yr^{-1} and NPP also greater by 0.55 Pg C yr^{-1}. The fluxes in Fire, Rh and NPP largely offset to minimize differences in NEE from age dynamics.

The question still remains – should there be an expectation for greater differences in NEE? Consider that deforestation (areal changes prescribed the same in $\mathbf{S}_{\mathbf{noage}}$ and $\mathbf{S}_{\mathbf{age}}$) occurs from the oldest to youngest age class in $\mathbf{S}_{\mathbf{age}}$, following greater to lower overall biomass, respectively. The deforestation flux is greater in the $\mathbf{S}_{\mathbf{age}}$ by only 0.04 Pg C yr^{-1} in 2000s compared to deforestation fluxes in $\mathbf{S}_{\mathbf{noage}}$, which makes sense given that low-biomass age classes are not preferentially deforested or harvested. By contrast, fire is not prescribed in LPJ-wsl v2.0 but it is simulated based on soil moisture and a minimum fuel load. It is not clear outright how age-dynamics affect soil moisture, but fluxes from fire would need to be proportional to the biomass in an age class. By definition in $\mathbf{S}_{\mathbf{age}}$, there is explicit representation of lower-biomass age classes (i.e., younger) than in $\mathbf{S}_{\mathbf{noage}}$, and a series of fires or disturbances within the grid cell would drive the age distribution towards younger states, exacerbating differences in downstream fluxes as well. That global NEE only changed marginally when simulating global age dynamics was a surprise, but explained by shifts in the carbon pools and compensatory fluxes, then the patterns appear to make sense. In light of these compensation effects, however, there is a great need to benchmark fluxes from critical feedbacks, particularly from fire in this case. It is beyond the scope of this paper to do so, and best available datasets, such as the Global Fire Emission Database (GFEDv4s; van der Werf et al. 2017) do not lend themselves to direct comparison with fire fluxes from LPJ. GFED includes fires from deforestation and land management that are tracked differently in LPJ-wsl v2.0 – as a land-use change flux, which cannot simply be added to the fire flux for direct comparison to GFED without double counting. In any manner, this issue is stated as a suggestion for future development and refinement.

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3.3.2 Global age-class distribution – contribution of fire and LUCLM to age distributions

Average ecosystem age, generated by the model, differed greatly among continents (Figure 7), with large areas of old-growth forests in Asia, Europe, North and South America skewing the distribution towards older ages. The largest area of young ecosystems was located in Africa and Australia (Figure 1), wherein age classes comprised an ~1:1 age to fractional area ratio of vegetated land (age-classes < 20 years comprise ~20% of the vegetated land area in Africa and Australia and age-classes < 40 years ~ 40% of vegetated land area; Figure 7).

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Ecosystem age by zonal band was oldest at boreal latitudes, followed by temperature latitudes, and youngest in tropical latitudes, which was primarily the results of frequent fires in simulated grassland ecosystems. The primary driver of zonal age distributions was Fire (Figure 8). According to results from the statistical model (Table 3), the average age difference due to fire among zonal bands in 1860 was 23 years between Boreal (older) and Temperature (younger) latitudes, and it was 32 years between temperature (older) and tropical (younger) latitudes. The difference in ecosystem age among zonal bands increased to 60 years in simulation year 2016 between boreal and temperate latitudes, while the difference in ages between temperature and tropical latitudes remained similar (31 yr age difference). There was a statistically significant decrease in zonal ecosystem age over time due to fire (Table 3), most likely from feedbacks due to enhanced fuel (biomass) production from CO_2 fertilization. The causes were not explored further because feedbacks between fire-climate-CO_2 are largely constrained by the fire module itself. The emphasis here is simply that fire was a major driver of age distributions and fire-age relationships had an apparent trend over time. Between simulation years 1860 and 2016, fire caused a total change in ecosystem age, integrated over the time period, by -1.5 years in boreal zones (negative values for a decrease in age), whereas the change was greater in temperate (-6.7 years) and tropical (-8.24 years) zonal bands (Table 3). The larger trend in temperate and tropical latitudes might be due to increasing warming temperatures in contemporary times, causing drier conditions more suitable for fire, or from increases in fuel loads from CO_2 fertilization. A more convincing argument would require support from additional factorial experiments to identify to the casual driver of the trend differences.

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After accounting for the effects of fire, LUCLM caused a much greater change over time in the zonal ecosystem age (Figure 9). Integrating from 1860 to 2016, LUCLM caused a zonal change in ecosystem age by -6.1 years in boreal zones, whereas the change in ecosystem age from LUCLM in temperate and tropical zones was -21.6 years, with no significant difference in the trend due to LUCLM among these zonal bands (Table 3). These patterns are consistent with the concentration of deforestation in the tropics and land-use change in temperate latitudes, as described by the forcing data (Hurtt et al. 2011, Hurtt et al. 2020).

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3.4 Global Demographic Effects on NPP and Rh

3.4.1 Simplification of LPJ-wsl v2.0 via a statistical model

The statistical model (flux = *B1* precipitation + *B2* temperature + $B3_{age}$ age-class; *See Sect. 2.3.6* for details) was able to estimate simulated NPP and Rh with great predictive power, with R^2 values between 0.95-0.98 (Figure 10). The predicted fluxes were at annual time scales, with annual variation being mainly driven by total annual precipitation and mean annual temperature, whereas the mean state (intercept) being predicted by the age class. The predictive power for a model of NEP was worse (R^2 between 0.60-0.65; SM Figure 1). The effect of precipitation, temperature and age-class on NEP was not consistent enough for robust predictions, but more specifically, the predictors had different effects on NPP versus Rh leading to poorer model fit. As it is, NEP is better derived as predictions of NPP minus predictions of Rh rather than having a standalone model for NEP.

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3.4.2 *The Effective Range of Predictors – assessing relative importance of demography on predicted fluxes*

The “Effective Range of the Predictors” were mapped to visualize spatial patterns of the range of effects, given observed values for the predictors (Figure 11). In essence, the effective range of the predictor is a measure of the dynamic range in the predicted flux due to changes in precipitation, temperature or demography. It is calculated as the gridcell-specific beta coefficient multiplied by the observed range of the predictor for a given grid cell, which helps constrain the effect of the predictor on the predicted flux to realistic values. For example, for the LPJ-wsl v2.0 grid cell at location [110.75 W 50.25 N], the ß estimate for the effect of precipitation on NPP was 0.0028, and the range of observed precipitation (based on CRU TS36) was 282 mm, then the effective range of the predictor on the flux was calculated as 0.0028*282 = 0.79 kg C m^{-2} yr^{-1}.

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The effect of precipitation on NPP was clearly greater in the central USA, central South America, and Eastern Australia (range of effect ~ 0.70 kg C m^{-2} yr^{-1} due to precipitation) than in other locations, and overall, precipitation had a stronger (positive) effect on NPP than on Rh (Figure 11). It was also clear from the maps that the direction of the effect of temperature on NPP was more spatially varied in the direction of effect (both positive and negative) than other predictors (Figure 11). The effects of precipitation and temperature displayed similar spatial patterns in both primary and secondary stands, which was a good indicator that the model was performing as expected because, within the LPJ-wsl v2.0 model, the distinction between primary and secondary stands is mainly to track land use histories and there was no reason, *a priori*, that climate effects should differ substantially between the two stand types.

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The effective range of demography on fluxes was generally lower than the effective range of precipitation and temperature, but there were regions where the range of demographic effects were just as important as, or greater than, the climate predictors. The demographic effect on NPP ranged between 0.30-0.60 kg C m^{-2} yr^{-1} in Eastern North America, Western Europe, Central Africa, Eastern China, Tropical Asia, and distributed smaller areas of South America (Figure 11), whereas it was at maximum ~0.10 kg C m^{-2} yr^{-1} in other regions. The higher demographic effect was predominately on secondary stands (Figure 12), but there was also a distinct absence of primary stands in these same areas (Figure 11) so it could not be said definitively if the higher demographic effect was due to a wider age distribution, and therefore a greater demographic effect, or simply due to the productivity of these locations.

3.4.3 Frequency distribution of demographic effects

The global mean demographic effect on NPP on primary stands was 0.078 ± 0.063 [0, 1.37] kg C m^{-2} yr^{-1} (μ ± stdev. [min, max]), whereas on secondary stands it was 0.160 ± 0.141 [0, 1.33] kg C m^{-2} yr^{-1}. There were differences in the spatial distribution of primary and secondary stands that led to the disparity in global mean values of the demographic effect. On primary stands, the distribution of age classes with maximum NPP flux was skewed towards the second (11-20 years) age class having the maximum NPP flux, whereas on secondary stands, the maximum NPP flux was in the first (1-10 years) and also in the second age class (Figure 12). The first class was categorized as 1-10 years, but in the presence of constant renewal, an age class can effectively be younger than an equivalent age class

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without such recurrent disturbance. Furthermore, on primary stands, fire is the only mechanism that creates young age classes, whereas land management also creates young age classes on secondary stands. It is possible for wood harvest, a form of simulated land management, to result in advanced regeneration of younger stands if harvest demand is met without 'clear-cutting' the prescribed fractional area under harvest. Currently, the model structure does not lend itself to say definitively the cause of the difference in the age class of maximum flux, but the only process that differs between primary and secondary stands is land management, so it is reasonable to assume that land management is the cause of the difference. In any manner, global values for age-effects for NPP on primary and secondary stands were also skewed towards greater values on secondary stands, but more due to the absence of primary stands in productive areas where secondary stands dominated (e.g., Eastern U.S.A.).

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Following a similar pattern, the demographic effects on Rh were greater on secondary stands than on primary stands (Figures 11 and 12), which could be partly explained by the differential coverage of secondary and primary stands, but also by historical land use. LUCLM leads to overall greater inputs to soil and litter carbon pools than does fire, and the latter is simulated in the same manner on secondary stands as on primary stands. In LPJ, wood harvest is only 60% efficient, leaving dead biomass 'residue' as a legacy flux. An increase of carbon in the litter and soil pools would add additional mass that can be respired during heterotrophic respiration, and which manifests as a larger demographic effect on Rh, ranging from 0.25 to 0.70 kg C m^{-2} yr^{-1} on the high-end (Figure 12).

4 Discussion

4.1 Distribution of Ecosystem Age on Earth

The LPJ-wsl v2.0 age-module simulates the age-class distributions on Earth resulting from fire, land use change, and wood harvest (Figure 13), while also simulating important demographics effects on NPP and Rh. Simulations demonstrate that fire and LUCLM have been driving the latitudinal age distribution towards younger states in contemporary times (Figure 8), suggesting an increasing role of age dynamics on global ecosystem functioning. Whereas time is the only mechanism that increases ecosystem age, any additional disturbance not explicitly modeled in this study will decrease age.

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The simulations omit widespread disturbances of windstorms, flood, pest and disease outbreak, selective logging, and other processes that would modify stand structure and function. For instance, small-scale logging activity is a dominant disturbance in South Eastern U.S.A. (Williams et al. 2016) but it is underestimated by the LUCLM driver data in this study ('LUHv2', Hurtt et al. 2020); otherwise the simulated age of secondary forests in this region (~100 years) would be lower and closer to inventory-based age estimates of these forests (< 50 years; *Figure 4 in* Pan et al. 2011b). In some locations, it is possible that our wood harvest priority rules (harvest oldest age class first) might lead to simulated stand ages that are younger than observed stand ages if other harvest rules were applied in practice, such as preferentially logging forests of forests with a goal of preserving the oldest forests from harvest. We evaluated the age distribution by continent simulated by LPJ-wsl v2.0 to the Global Forest Age Database (GFAD v1.0, Poulter et al. 2018), which is derived from country-level inventory data. The comparison shows that the simulated

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ages are consistently older than the GFAD dataset (SM Figure 11). Furthermore, the fire module has been well evaluated at global scale (Thonicke et al. 2001) but it needs improvement because it is overly simplistic and underestimates global burned area (Hantson et al. 2020). It is more likely that effects of fire are much greater than simulated in this study. This study likely underestimates disturbances rather than overestimates them, and as such, these simulations overestimate ecosystem age. But again, additional disturbances would only lead to younger age classes, enhancing the role of age dynamics in regional and global carbon cycles.

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Our model developments are not optimized to match observations, although we are working toward this end. Future goals are to assimilate stand-age related data, such as remotely-sensed canopy data and stand index growth curves, to align model processes with observations. Even with these caveats in mind, the findings presented retain utility as insight into the way age-class dynamics integrate into our broader understanding of global carbon dynamics. Ecosystem demographics likely play a larger role than suggested here, and on regional scales, demographic effects on NPP and Rh are already identified by this study as more important in East Asia, Tropical Asia, Europe, Central Africa, Eastern North America, and Tropical South America than they are in other regions, where average ecosystem ages are much older.

4.2 Age Dynamics Increase Turnover

In an analysis by Friend et al. (2014), it was determined that demographic processes (age-dependent mortality and turnover) influence carbon residence time (1/Turnover), which was found to be a major source of uncertainty in future projections by global ecosystem models. In this study, it was demonstrated that simulation of age classes led to a ~40 Pg C shift from live vegetation to the soil-litter pool, effectively an increase in biomass turnover. That turnover increases when explicitly simulating ageclasses is a natural expectation, but the magnitude of the simulated turnover between carbon pools less certain until detailed benchmarking is conducted. Further, relaxation times, or the time to return to a previous state, were up to 30 years in the no-age simulation ($\mathbf{S_{noage\_event}}$; Figure 5) but relaxation times were less than 10 years when simulating age classes, suggesting that uncertainty in carbon residence time could potentially be reduced by improving representation of demographics in models. Omitting age class representation in models can leave long-lasting patterns in simulated fluxes that could inflate land-use change fluxes at global scales when considering legacy fluxes from past land-use change (Pongratz et al. 2014). The current state of knowledge is that fluxes from gross land-use change and land management cause greater-than-expected land use fluxes (Arneth et al. 2017), but existing models that estimate the global land use flux (Arneth et al. 2017, Le Quéré et al. 2018) do not include age dynamics. If resiliency is inversely proportional to relaxation times (a quicker return to previous states is represented by shorter relaxation times, therefore greater resiliency; Pimm 1984, Tilman and Downing 1994), then instead of land-use change fluxes being 'greater than assumed' (Arneth et al. 2017), we might rethink the land as being 'more resilient than expected' when demographic effects are considered at large scales.

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4.3 Forecasting Demographic Effects with a Simplified Statistical Model

The modeling community has made increasing effort to simplify complex models using a traceability framework (Friedlingstein et al. 2006, Xia et al. 2013). Statistical emulators, from matrix models (Huang et al. 2018) to accounting-type statistical models, which track individual carbon pools (Xia et al. 2013, Ahlström et al. 2015), have been developed to reduce the dimensionality of simulated state variables. However, statistical modeling by linear regression can be a more straightforward approach, as long as the statistical model shows promise.

We found that LPJ-wsl v2.0 fluxes of NPP and Rh could be predicted at annual timescales by three terms, precipitation, temperature and age-class. Part of the success of the data model came from allowing coefficients to vary by grid cell. This allowed the intercept (age-class) term to effectively capture grid cell level variation in soil texture (which influences soil hydrology and plant available water), PFT composition and cloud cover. Another insight was that climate and age-class had differential effects on NPP versus Rh, which makes sense and ultimately led to poorer fit of the NEP model (NEP = NPP – Rh). It might have been possible to improve upon the NPP model further by separately modeling GPP and Autotrophic Respiration (NPP = GPP – Ra) because climate might also have differential effects on GPP than on Ra, but suffice to say that the NPP statistical model was robust.

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Although unexplored in this study, the spatial datasets of predictor coefficients could be used within an emulator (Xia et al. 2013, Ahlström et al. 2015) to forecast NPP and Rh, while exploring the effects of extreme climate scenarios (Reichstein et al. 2013) and changes in ecosystem demography from land-use change and land management. Such application would allow for a much quicker exploration of scenarios and could include a more explicit treatment of uncertainty that would otherwise be too costly for the simulation model in terms of computing time. With regards to climate, the spatial dataset of precipitation coefficients has an equivalent meaning to spatial maps of climatic sensitivity. In fact, the maps of the effective range of precipitation on NPP (Figure 11) show areas where the precipitation effect is largest, notably in semi-arid biomes – a biome that is known to be highly sensitive to precipitation and has been shown to play an important role in the inter-annual variability of global-scale fluxes (Poulter et al. 2014, Ahlström et al. 2015). But what if, in a given year, semi-arid biomes received their maximum annual precipitation, while every other biome received its lowest annual precipitation – can anomalously high annual precipitation and high productivity events in some regions overcome anomalously low precipitation and low productivity events in other regions? Are the effects of different climate scenarios dependent on demography? These types of question are best suited for exploration within a simplified statistical model that maintains fidelity to the process-based model because effects of climate on fluxes can be explored quicker, easier, and with a better treatment of statistical uncertainty.

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4.2 Vector Tracking of Fractional Transitions (VTFT) – modeling age classes in global models

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The VTFT approach simulated classic demographic responses in NPP and Rh (Figure 4), a differential in younger age classes that led to a larger carbon sink in the youngest stands. These demographic responses are inherent within the original formulation in LPJ; that is, establishment rates and the process of self-thinning of stand density over time as plants grow and compete (for space, light, water resources) have been unchanged. In the original formulation

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of LPJ-wsl v2.0 (prior to this study), and under a hypothetical scenario where a disturbance clears the biomass from the entire grid cell (0.5° ~ 2,500 km^2), the resultant evolution of stand structure and fluxes would produce the same pattern as in the age-module, such as the age-NPP pattern from Figure 4. It is often the case, however, that smaller disturbances (<< 2,500 km^2) occur regularly as opposed to a much larger disturbance the size of the entire grid cell. As such, in the original formulation of LPJ, the potential benefits of demographic responses are often masked (as demonstrated in *Section 3.2.2*; Figure 5). One can then say that the VTFT age-module reveals intrinsic demographic responses and model behavior that would rarely emerge otherwise.

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Total runtime for global age-class simulations (**S_{age}**) was ~8 hrs on 32 Intel Xeon CPUs, including spinup to transient simulations, whereas the total runtime for the no-age simulations (**S_{noage}**) was ~3 hrs. On a limited sample of single grid cell simulations, there was a 4- to 6-fold increase in runtimes, but not all grid cells require simultaneous tracking of every age-class so the increase in runtime of global simulations was lower than expected from per-gridcell estimates.

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4.3 Opportunities for Improving Modelled Age-dynamics

In order of priority for improvement of the age-module: 1) improve age class growth rates to align with observations, 2) improve representation of disturbances, 3) improve representation of early- and late-successional plant species and add vertical structural complexity such as understory/overstory canopy. Below, we provide suggestions and examples from the literature as how these improvements might be accomplished.

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Inventory data or remotely-sensed observations of canopy height provide a potential means for constructing age-height curves (Croft et al. 2014, Yue et al. 2016) to inform growth rates by age class. Alternately, Hiltner et al. (2020) recently optimized mortality rates in an individual-based model at different forest successional stages by using satellite-derived proxies of tree mortality (Hiltner et al. 2020); their optimized model was shown to improve representation of forest states during post-disturbance regrowth. Another LPJ variant, the LPJmL4 DGVM, also underwent parameter optimization to improve spatial patterns of tree cover and forest turnover (Forkel et al. 2019). Different solutions are possible, and not all of them require parameter optimization, but the aim should be to align simulated forest structure and function with observations.

Our comparison of simulated versus inventory forest age distributions by continent (SM Figure 11) clearly show that LPJ-wsl v2.0 overestimates stand age. A potential solution to this discrepancy is to incorporate additional disturbances within the model to help simulate age distributions more consistent with inventory (Pan et al. 2011a) and satellite (Pugh et al. 2019b) data and contribute to more scientifically relevant questions. Firstly, general improvement of the fire module in LPJ-wsl v2.0 is necessary to match burned area observations. One such solution is to use a suite of satellite data products to prescribe burned area instead of simulating fire, which could help improve simulated stand age distributions in areas where fire is observed but not well simulated mechanistically (Poulter et al. 2015). Modeled disturbances need not be complex to explore their effects on age distributions, they only need to

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reset a fractional area to the youngest age class. For example, windstorms from Hurricanes are known to be a large disturbance of Eastern North American forests (Dale et al. 2001). Data on Hurricane return intervals and locations of landfall in Eastern North America have been available for some time (Keim et al. 2007), and could be used to prescribe a periodic resetting of age classes to assess the demographic effect of Hurricanes on ecosystem function. In another example, forest gaps represent areas of high production because of high resource abundance relative to the surrounding areas. The distribution of forest gaps also has a predictable power-law relationship with size of the gap (Asner et al. 2013), which can be allowed to vary across and within regions (Asner et al. 2013, Espírito-Santo et al. 2014), and this fact lends itself well for representing gaps within the framework of the current age-module. Many disturbances can be prescribed based on observed forest disturbance rates (Pugh et al. 2019), but prescribed disturbance patterns typically sacrifice capacity to simulate under novel conditions so there are tradeoffs to consider.

There are limitations to the current framework of the model, which are more difficult to overcome and will require more effort in model development. In this version of the model, plant composition and competitive dynamics in young age classes are not representative of early successional dynamics because there is a lack of plant trait variation in the current set of PFTs that could otherwise represent a wider range of growth strategies, turnover, and production (Pütz et al. 2011, Fischer et al. 2016, Miller et al. 2016). There is also no height variation within an age class, for lack of a radiative transfer model; each age class in LPJ-wsl v2.0 is an even-height stand. Demographic patterns in this study (age-NPP, age-Rh, relaxation times by age class) will inevitably differ when, and if, additional trait and height variation is incorporated into the model. Recent model developments in JSBACH4 (Nabel et al. 2019) and ED-2.2 (Longo et al. 2019) could point the way forward for incorporating a greater amount of vertical heterogeneity in LPJ-wsl v2.0, as well as in other models.

5. Code and Data Availability

LPJ-wsl v2.0 model code, in its entirety, is freely available at <https://github.com/benpoulter/LPJ-wsl_v2.0>, and a permanent version of the model code is deposited at Zenodo <DOI: 10.5281/zenodo.4409331>. Code used for analyses and figure production are available at <https://github.com/lcalle/VTFT_demography>. Associated data necessary to reproduce the analyses and figures, as well as a copy of the analysis code is permanently archived at the Dryad Digital Repository <https://doi.org/10.5061/dryad.k6djh9w4x>.

6. Author Contributions

LC and BP designed the model experiments and LC carried them out. LC developed the code for the age-class module and performed the simulations. LC and BP prepared the manuscript.

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Table 1. Age class widths corresponding to two different simulation age class setups in LPJ-wsl v2.0. The age-class codes are referenced in Figures.

	Age Widths (years)	
Code	**Unequal Bins**	**10-yr Equal Bins**
1	1-2	1-10
2	3-4	11-20
3	5-6	21-30
4	7-8	31-40
5	9-10	41-50
6	11-15	51-60
7	16-20	61-70
8	21-25	71-80
9	26-50	81-90
10	51-75	91-100
11	76-100	101-150
12	+101	+151

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Table 2. Description of LPJ-wsl v2.0 simulations in this study, corresponding objectives and related science questions. Land-Use Change and Land Management (LUCLM, LU).

Simulation	Description	Objective and Questions	*Structure/Processes Included* Age classes	Fire	LUCLM
Single-cell					
S_{age_event}	Idealized simulations of a deforest, abandon, and regrow event in British Columbia, CAN [121.25W 57.25N]	Evaluate recovery dynamics of a single regrow event. Do age dynamics influence relaxation times?	✓	✓	✓
S_{noage_event}			*x*	✓	✓
Regional					
$S_{unequalbin}$*	Idealized simulation with 5% of grid cell cleared annually to create a wide age-class distribution in mixed broadleaf and evergreen temperate forests of Michigan (MI), Minnesota, and Wisconsin (WI) of U.S.A.	Does the model capture 'classic' demographic patterns in stand structure (tree density and height) and function (NEP, NPP, Rh)?	✓*	*x*	*x*
$S_{10yrbin}$‡			✓‡	*x*	*x*
Global					
S_{noage}	Standard-forcing factorial simulations at global scale.	Do age dynamics influence global stocks and fluxes?	*x*	✓	✓
S_{Fire}		What is the relative contribution of Fire and LU to ecosystem age?	✓	✓	*x*
S_{LU}		Are demographic effects evident in fluxes, and where is the effect greatest?	✓	*x*	✓
S_{FireLU} (S_{age})		What is the relative contribution of climate versus demography on fluxes?	✓	✓	✓

* unequal age width simulation. Age widths as described in Table 1

‡ 10-yr interval age width simulation. Age widths as described in Table 1

Table 3. Linear trend statistics by zonal band from LPJ-wsl v2.0 simulations, based on model (age = $\beta 0$ + $\beta 1$*year) where year at 1860 is indexed at 1. Coefficients listed as μ ± S.E. All d.f. are 113 and $p < 0.001$.

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Zonal Band	Simulation	$\beta 0$	$\beta 1$	R^2
Boreal	Fire Only ($\mathbf{S_{Fire}}$)	141.7 ± 0.01	-0.0098 ± 0.0002	0.95
	Fire and LUCLM ($\mathbf{S_{FireLU}}$)	139.7 ± 0.13	-0.0388 ± 0.0019	0.78
Temperate	Fire Only ($\mathbf{S_{Fire}}$)	118.5 ± 0.05	-0.0525 ± 0.0008	0.98
	Fire and LUCLM ($\mathbf{S_{FireLU}}$)	112.6 ± 0.21	-0.1383 ± 0.0032	0.94
Tropics	Fire Only ($\mathbf{S_{Fire}}$)	95.9 ± 0.06	-0.0429 ± 0.0009	0.95
	Fire and LUCLM ($\mathbf{S_{FireLU}}$)	88.9 ± 0.16	-0.1382 ± 0.0024	0.97

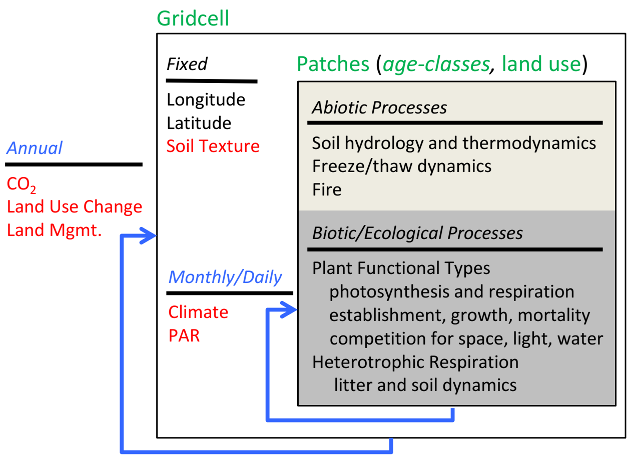

Figure 1. LPJ-wsl v2.0 model structure of inputs (red), time-steps (blue) and the level at which state variables are tracked within grid cells and sub-gridcell age classes (green), such as age classes or land uses. Simulation of abiotic, biotic and ecological processes occurs at the scale of an age class.

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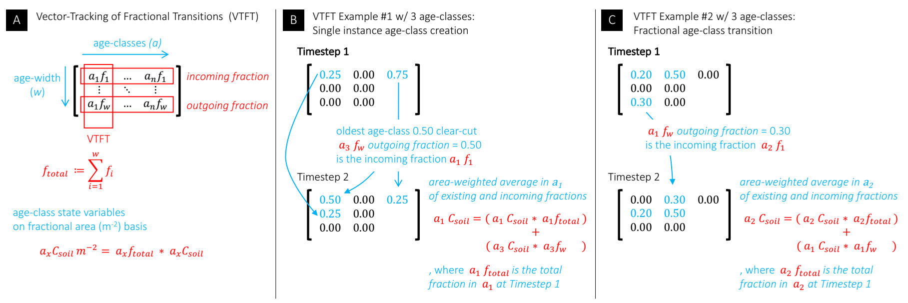

Figure 2. Methodological examples of the matrix based method called Vector-Tracking of Fractional Transitions for computationally-efficient simulation of age classes in large-scale models. (a) Hypothetical matrix of VTFT vectors of fractional areas (*f*). The total area of the age class is the sum of the fractional areas in the corresponding VTFT vector. State variables are calculated on area basis by accounting for the fractional area of the age class, in this example C_{soil} is the carbon in soil. (b) An example of the VTFT method for a newly created age class by clear-cut wood harvest. An area-weighted average updates age-class state variables in the youngest age class using the preceding total fractional area of the age class and the incoming fraction. (c) A VTFT example for a fractional age-class transition. An area-weighted average updates state variables in an age class using the preceding total fractional area of the age class and the incoming fraction from the younger age class.

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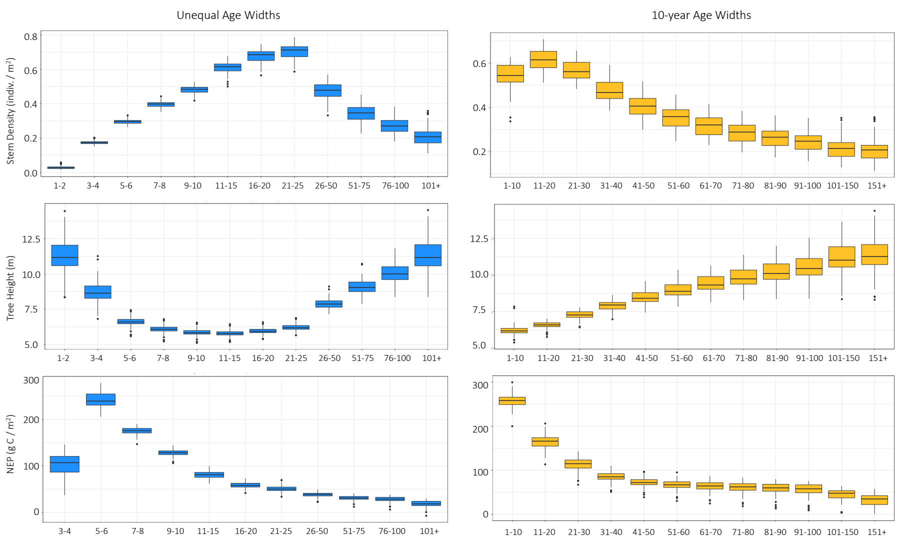

Figure 3. Boxplots by age classes (x-axis, *in years*) from LPJ-wsl v2.0 simulations for U.S. States of MI, MN, WI. (blue, left) Age classes defined with *unequalbin* age widths (Table 1); small age widths in the youngest age classes towards progressively larger width age classes. Density peaks in the 21-25 year age-class and NEP peaks in the 5-6 year age-class. For average tree height (middle row), large tree height in the youngest age class represents the 'survivor' trees; average tree height decreases as the density of establishing saplings increases. (gold, right) Age classes in *10-yr-equalbin* age widths (Table 1), the standard age-class setup used in global age-class simulations. Peaks in Density and NEP roughly follow the age class patterns when finer age widths are employed (blue, left).

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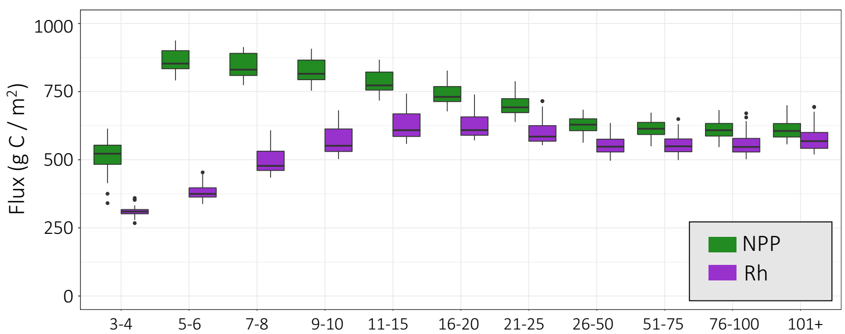

Figure 4. Boxplots of NPP and Rh by age classes (x-axis, *in years*) from LPJ-wsl v2.0 simulations for U.S. States MI, MN, WI. Age classes defined with *unequalbin* age widths (Table 1); small age widths in the youngest age classes towards progressively larger age widths.

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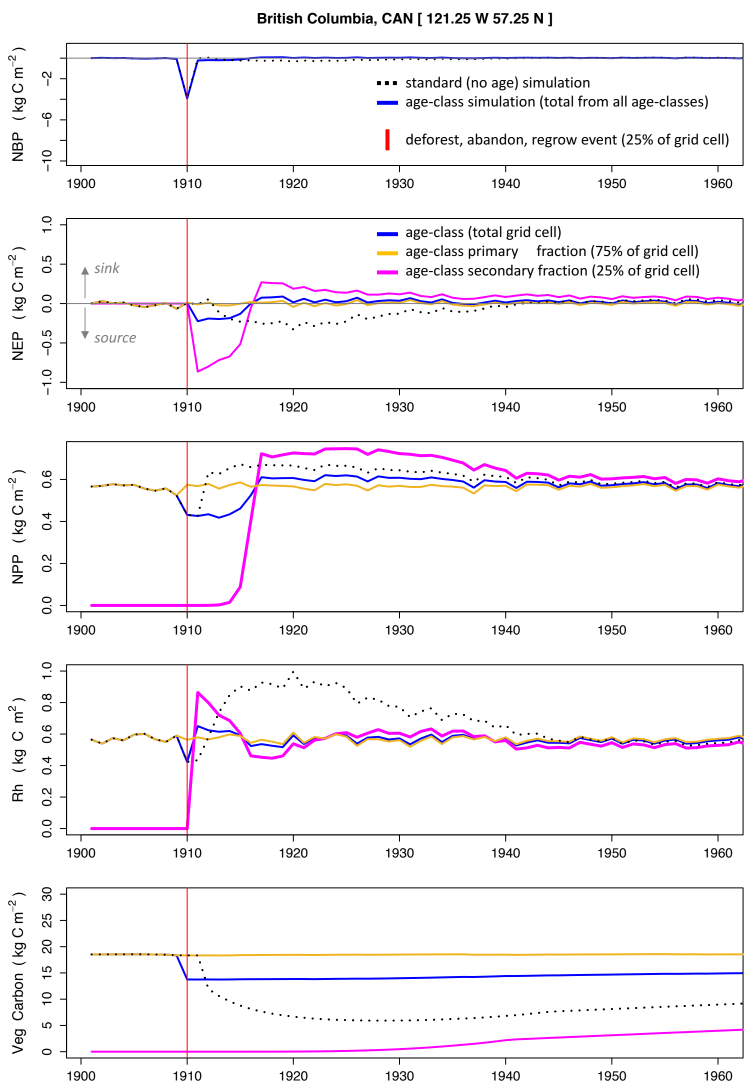

Figure 5. A time-series comparison between the standard LPJ-wsl v2.0 simulation (S_{noage_event}) and the age-class approach (S_{age_event}) in an idealized single-cell simulation of a deforestation, abandonment, and subsequent regrow event. x-axis is the simulation year. See Table 2 for simulation details.

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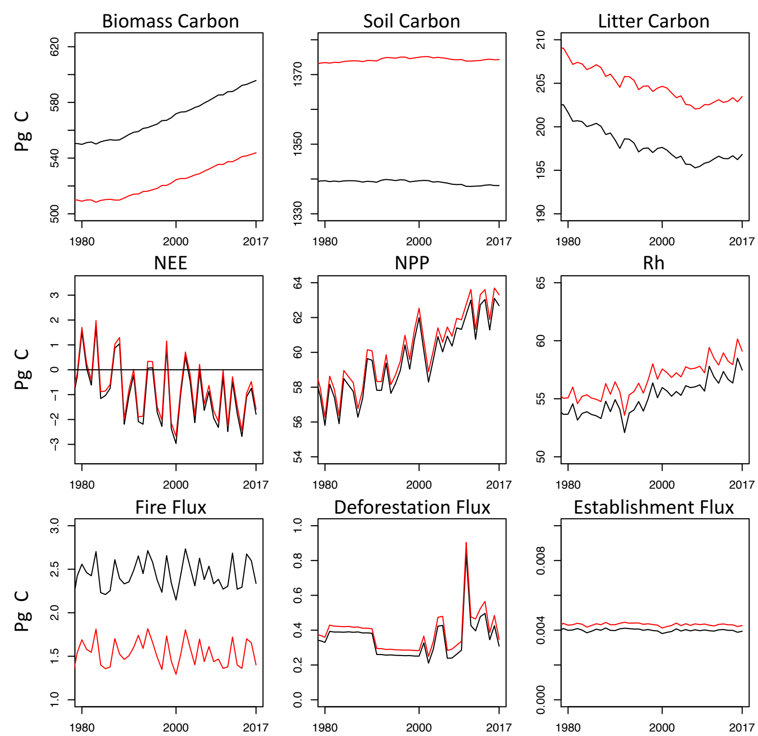

Figure 6. Time-series of global carbon stocks and fluxes from LPJ-wsl v2.0 simulation *without* age classes (black lines) compared against simulations *with* age classes (red).

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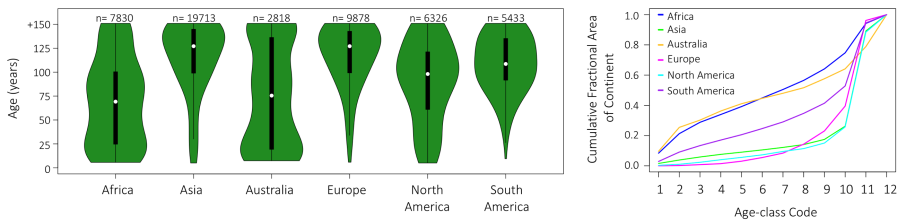

Figure 7. Age class distributions by Continent. (left) Violin plots of ecosystem age by continent averaged over 2000-2010, based on LPJ-wsl v2.0 simulations. Violin plots show the distribution of data points (green), inter-quartile range (black box) and the median value (white circle). The number of vegetated 0.5° grid cells in each continent are above plot. (right) Cumulative fractional area in continent by age classes. Age-class codes, lowest (youngest) to greatest (oldest), correspond to the *10-yr-equalbin* age-class setup (Table 1).

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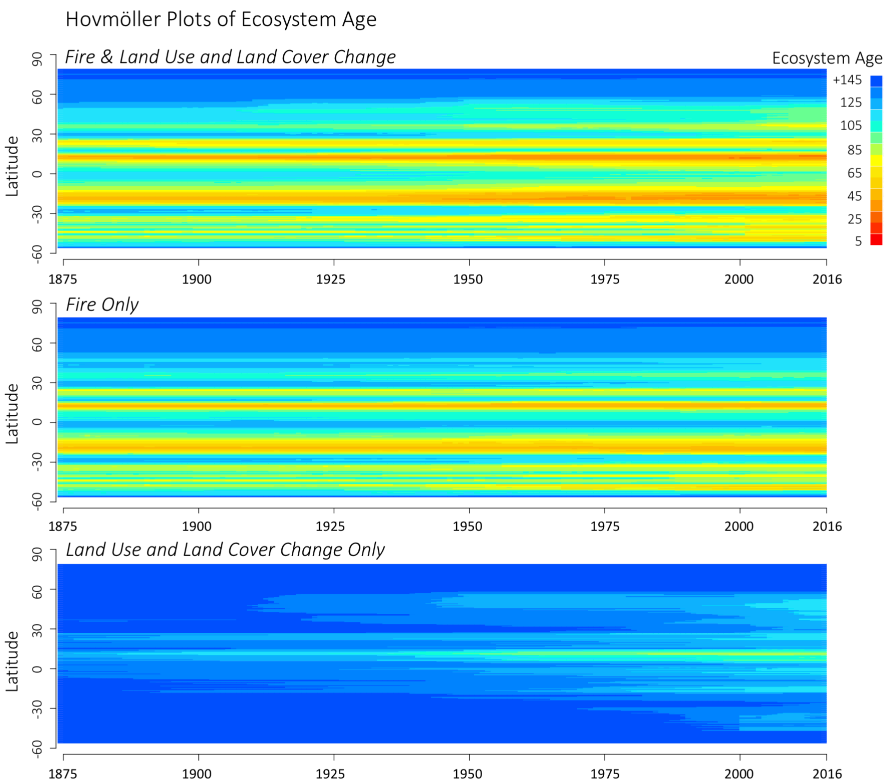

3115 **Figure 8. Zonal ecosystem age versus year based on LPJ-wsl v2.0 simulations using full forcing (top), only fire (middle), or only land use and land cover change (bottom).**

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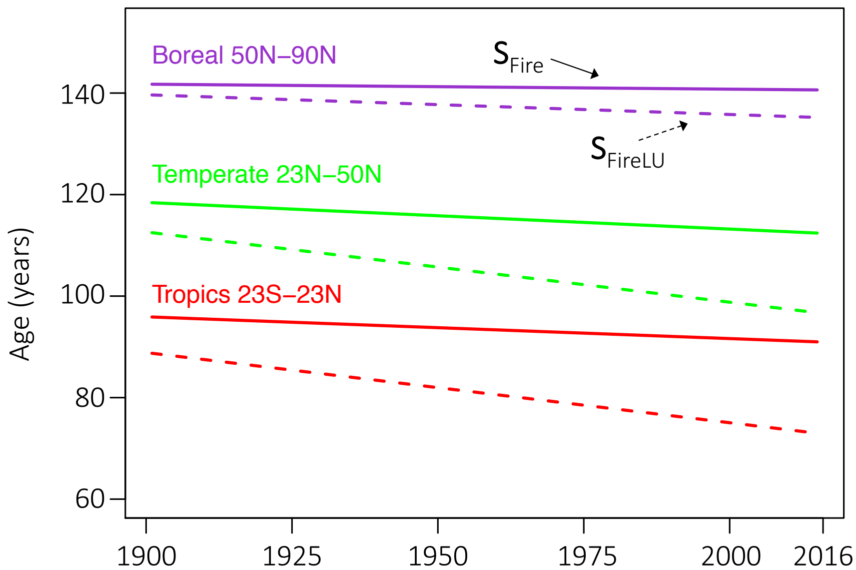

Figure 9. Trend in ecosystem age by zonal band for LPJ-wsl v2.0 simulation with only fire (S_{Fire}, solid lines) and with both fire and LUCLM (S_{FireLU}, dashed lines). Fire causes zonal bands to differ in ecosystem age by ~23 years, and decreases the average age by 0.009 to 0.054/yr. LUCLM decreased ecosystem age at rates up to 3-times the rate of fire, from 0.038/yr in boreal zones to 0.138/yr in temperate and tropical zones.

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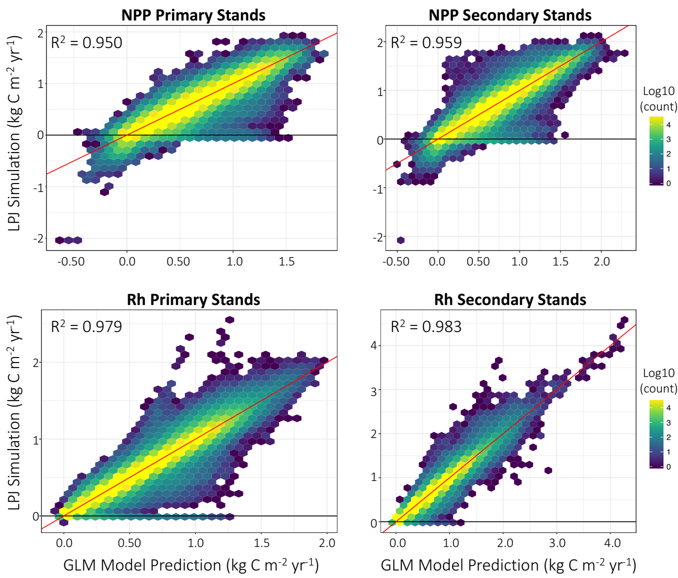

Figure 10. Annual fluxes (NPP, Rh) (2000-2017) from LPJ-wsl v2.0 simulations versus predictions of LPJ-wsl v2.0 fluxes based on a generalized linear model (flux = precipitation + temperature + age-class); coefficients were allowed to vary by grid cell, in essence, reducing the effect of variation in plant composition, soil texture and hydrology. Coloring is by density of grid cells on a log scale; diagonal red line is the 1:1 correspondence line. The simplified statistical model can simplify the dynamics in the global vegetation model, with coefficients from the GLM helping to determine the relative importance of a small set of predictors.

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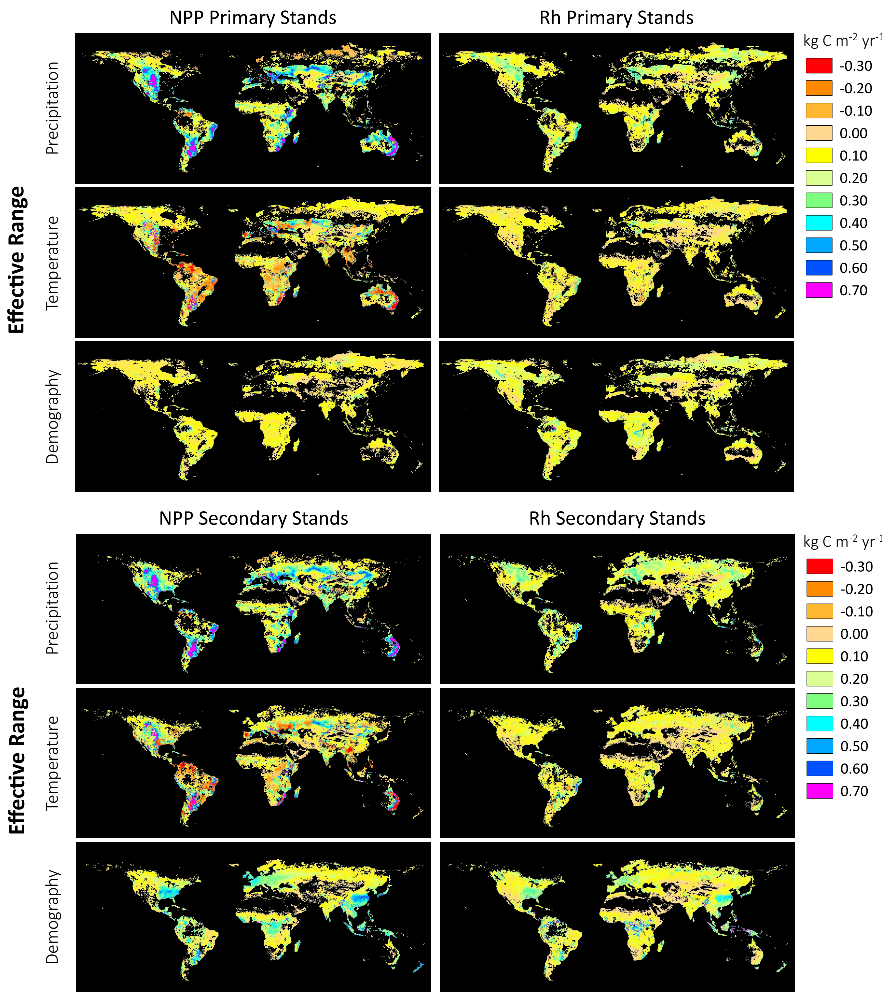

Figure 11. Global maps of the Effective Range of the Predictors (precipitation, temperature, demography) on LPJ-wsl v2.0 fluxes (NPP, Rh); black is zero values or no-data. The Effective Range of the predictor is calculated as the gridcell-specific beta (ß) coefficient multiplied by the observed range of the predictor variable for the grid cell, for years 2000-2017. Units are on the scale of the predicted flux (kg C m^{-2} yr^{-1}). In these maps, an emphasis is placed on the effective range of the predictor rather than the absolute value of the coefficient, although these too can be mapped for forecasting purposes. See *Sect 2.3.6* and *Sect 3.4* for additional details.

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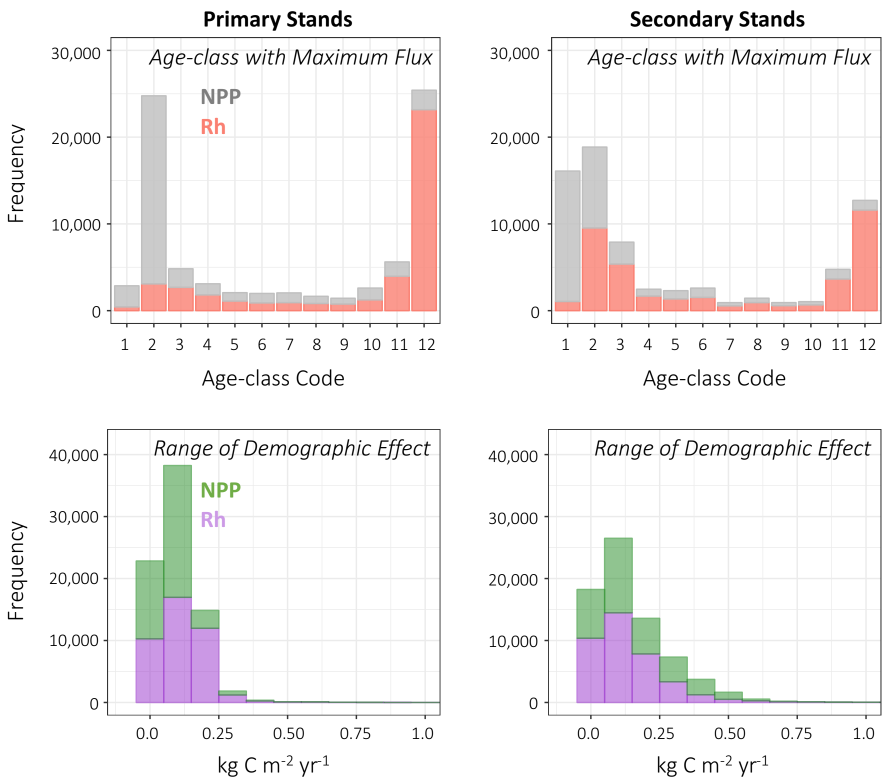

Figure 12. Stacked frequency plots for NPP, Rh on primary and secondary stands. (top row) Global frequency of age classes with the largest flux (NPP, Rh), relative to other age classes in the grid cell. Age-class codes, lowest (youngest) to greatest (oldest), correspond to the *10-yr-equalbin* age-class setup (Table 1). (bottom row) Global frequency of the range of the demographic effect on fluxes, bin width is 0.10 kg C m^{-2} yr^{-1}. An example interpretation, on primary stands, (top left) NPP is greatest in the second age class and (bottom left) the demographic effect on NPP is < 0.25 kg C m^{-2} yr^{-1}.

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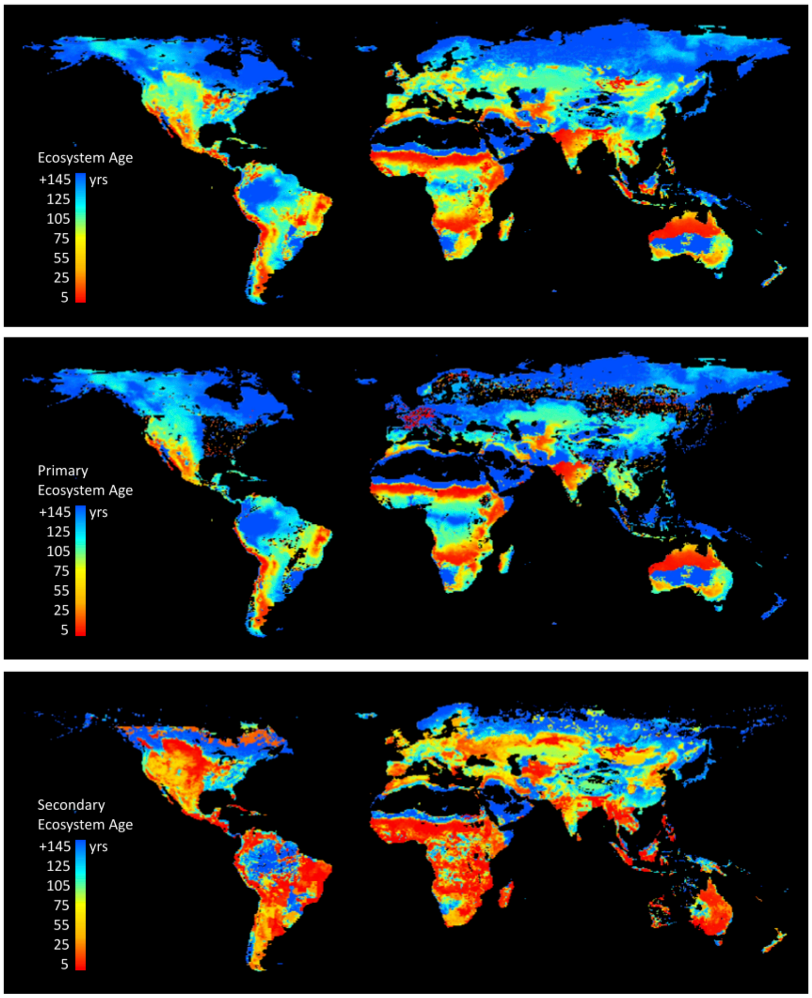

Figure 13. LPJ-wsl v2.0 simulated global distribution of ecosystem ages, defined as the time since disturbance by fire and/or land-use change and land management (LUCLM) in year 2016. (top) Average age of the natural ecosystem, scaled to the area of natural lands within 0.5° grid cells. (middle) Average age of primary Ecosystems only, wherein only fire creates age structure, scaled to the area of primary lands. (bottom) Average age of secondary Ecosystems only, wherein fire and LUCLM creates age structure, scaled to the area of secondary lands.

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