Reviewer Ensheng Weng

Dear Ensheng Weng,

We would like to thank you for your interest in our work, and for providing valuable comments that will significantly improve the quality of our publication. Below we provide a point-by-point reply to your comments, formatted in italic. Additions to the manuscript are formatted in bold italic and line references refer to the updated version of our manuscript.

Best regards,
On behalf of all authors,

Jette Elena Stoebke and David Wårlind

In this version of the revised manuscript, the authors switched the theme from model description to the evaluation of three schemes of forest tree crown organization. They implemented two new crown organization schemes (PPA, and Spatially-explicit canopy, SEC), in addition to the original scheme in LPJ-GUESS (stretched crowns that overlay each other according to their heights). For the stretched crown, they have disturbance ON and OFF. So they have four schemes compared in this paper. I am ok with this change and find it is very interesting to test how the settings of crown organization affect simulations of forest dynamics. Gap models keep all details, while PPA highly simplified them by assuming "perfect plasticity" of crowns in filling the canopy layers. The ED model scheme assumes stretched crowns in an adult tree-sized patch (same as LPJ-GUESS's original scheme) so that to solve the mean of many tree-sized patches. The authors proposed a relatively "strict" crown scheme here to realistically model light penetration to the understory layers.
I only have minor questions that need author to clarify. The page and line numbers are from the change tracked version (ATC2).

Q1**.** Abstract section. Since the major theme is changed, it is better for the authors to write a new abstract so that readers can quickly catch the major ideas of this paper.

*Reply**:** The manuscript retains the same model setups, analyses, and resulting figures and tables as the original version. The primary change concerns terminology: what was previously referred to as PPL (Perfect Plasticity-Like) has been renamed to PPA following a reviewer's suggestion that the approach is consistent with the original PPA framework. Aside from this, the revisions consist mainly of additional explanations and clarifications. The core concepts and results remain unchanged. In response to your point 12, we have updated the abstract.*

Q2**.** Lines 106~107: LPJ-GUESS distributes each cohort's leaf area evenly across entire patch, disregarding the actual crown area, which results in a uniform light distribution
I think the major issue for the "stretched crown" is all the trees in a patch, except the tallest one, is shaded, instead of "a uniform light distribution" because, for PPA, the understory light is uniformly distributed.

Reply: We agree that the primary limitation of the "stretched crown" representation is that the tallest cohorts gain a disproportionate advantage over smaller cohorts. This can lead to situations where a single large cohort shades all others to such an extent that it becomes the only surviving cohort, as described in lines 147-149 (all lines refer to the diff document). To clarify this, we have revised the description of the standard LPJ-GUESS approach by specifying that it results in a ***horizontally*** *uniform light distribution on lines 105.*
In the standard PPA approach, the understory of each canopy layer that horizontally fills that patch receives the average light that penetrates the layer(s) above, making the light for each layer uniformly distributed. For each layer, the individual cohorts take up individual amount of light depending on their LAI. In contrast, our PPA implementation does not assume horizontal uniformity. As described in lines 186-210 and illustrated in Fig. 1c, light interception is calculated for each unique vertical column, thereby preserving spatial variability in light conditions.

Q3**.** Line 156, equation 2: It means all the individuals in a cohort that is pushed to the lower layer will be killed. This is a very strong assumption. Usually trees can be suppressed many times in their life time. See Farrior et al. 2016. Science, Dominance of the suppressed: Power-law size structure in tropical forests.
I understand it is for directly applying the rules of "self-thinning".

*Reply**:** In the standard LPJ-GUESS configurations (i.e. the LPJ and LPD approaches), Eqn. 2 influences the self-thinning mortality of individual cohorts only when their total horizontal crown area exceeds the maximum allowed crown area (CAmax,i), which in these schemes is equal to the patch area. In contrast, in SEC and PPA, CAmax,i is assigned at establishment (see lines 179-180 and Fig. 2), and self-thinning begins when a cohort's total crown area exceeds this limit plus the crown area of an additional tree individual of the cohort. Importantly, none of the schemes explicitly reassign cohorts to lower canopy layers. Thus, Eqn. 2 does not suppress cohorts based on their position in a "layer". Instead, growth efficiency governs mortality risk. Cohorts that are suppressed by taller trees experience reduced growth efficiency, which in turn increases their probability of mortality. To make this clearer we have updated lines 152-155 to read "****Self-thinning was triggered only when CAi > CAmax,i, implemented as an increased probability of mortality (mort_self); otherwise, no self-thinning occurred (Eqn. 2). This self-thinning response was determined solely by the crown area of the individual cohort and did not depend on the total crown area of all cohorts within the patch****."*

Q4**.** Page 9, Table 1, about the PFTs, what parameters are used to define shade tolerant and intolerant PFTs? Usually, they are defined by parameters of photosynthesis, respiration, and mortality rates. These parameters can be put into this table. It will make it easier to understand simulated forest dynamics.

*Reply**:** We have added the remaining three parameters distinguishing shade-tolerant from shade-intolerant PFTs to Table 1. We also included an explanation in the table caption noting that, while these parameters contribute to differences between shade-tolerant and intolerant PFTs, they were not included in the model sensitivity analysis because they are not directly influenced by the new canopy schemes.*

Q5**.** Page 13, Lines 319~320: “LPJ allocated an overly large fraction of the AWP flux to large trees, while LPD disproportionately assigns a larger fraction of the AWP flux to smaller trees.”
This sentence suggests the model calculates total wood growth and then allocated it to different cohorts. I think it should be calculated cohort by cohort.

*Reply: This is not the case. The sentence has been revised (line 323-326) to clarify that productivity is calculated independently for each cohort. It now reads: “**Overall, larger tree cohorts in LPJ accounted for an overly large share of the AWP flux, whereas in LPD smaller tree cohorts contributed disproportionately to the AWP flux.**”*

Q6**.** As for the wood growth in different sized trees, it can be affected by tree sizes depending on the allometry equations. What allometry equations are used in this model?

Reply: The allometric relationships follow the “pipe model” (Shinozaki et al. 1964a,b; Waring et al. 1982), in which tree aboveground structure is represented by a cylindrical stem consisting of an inner heartwood core surrounded by a sapwood layer of constant thickness, and a cylindrical crown (i.e. foliage) of specified diameter. Sapwood and heartwood are assumed to have the same constant density, shared across all tree PFTs. Tree height is then derived from the relationship between sapwood cross-sectional area and total leaf area, expressed as:

height = cmass_sap / (wooddens × cmass_leaf × sla) × k_latosa

*In the model description section, it has been added that LPJ-GUESS uses the allometric relationships of the pipe model formulation (line 120-122). “**Instead, the scheme represents canopy structure purely in the vertical dimension, using cohort bole and total height derived from pipe model–based allometric relationships (Shinozaki et al. 1964a,b; Waring et al. 1982; Smith et al. 2001, 2014).**”*

Q7**.** Section 3.2 Coexistence (Pages 16~19).
How are the coexistence maintained? I ask this question because for the individual-based competition, the community tends to converge to one PFT. For maintaining stable coexistence of different PFTs, they must have negative feedback (i.e., intra-specific competition is stronger than inter-specific competition)
Is the “coexistence” generated by the disturbances in different patches?

Reply: As discussed in the manuscript (lines 447-473), coexistence in the standard LPJ-GUESS framework (LPD) is primarily driven by recurring patch-destroying disturbances, which periodically create light conditions on the forest floor that favour the establishment of shade-intolerant PFTs. In their absence, the system tends to become dominated by a single shade-tolerant PFT, as shade-intolerant species rarely have opportunities to regenerate. In contrast, both SEC and PPA allow for the formation of canopy gaps, creating more frequent and spatially heterogeneous light environments that facilitate the establishment of shade-intolerant PFTs. The characteristics and frequency of these gaps differ between the schemes, as described in the manuscript (lines 156-185; Fig. 2).

Q8**.** Section 3.3 Re-establishment

“recruitment layer” is mentioned here but not explained/defined. For the cohort-based demographic vegetation model, all individuals (including new-born seedlings) are represented by cohorts that define individuals with their sizes. What does a “recruitment layer” mean?

Reply: Recruitment layer is defined as cohorts with a DBH smaller than 15 cm (see line 294-295).

Q9**.** Section 3.4. patches
This reminds me a question of patch dynamics. In the model, how the patches are generated and removed? All the simulations with different crown organization schemes are based on dynamical patches?

Reply: New patches are not generated through natural processes in LPJ-GUESS, instead, the number of patches representing natural systems is fixed at the start of a simulation (see lines 221-223). Changes in patch number only occur in response to land-use change, where the area allocated to natural vegetation increases or decreases. This contrasts with models such as the PPA model FATES, in which the number of patches can vary dynamically over the course of a simulation as a result of natural processes.

Q10**.** 425~426 “PPA-based models delay thinning until the light environment is fully saturated”. Actually, in BiomeE (and LM3-PPA), self-thinning starts at forest closure (CAI>= 1- eta), where the new growth of crown area is greater than the crown area reduction due to mortality.

*Reply: We acknowledge that self-thinning and mortality processes differ among models that implement PPA. For example, BiomeE applies a U-shaped, calibrated mortality function that incorporates background mortality rates specific to each PFT, canopy position, shading effects, and tree size. To reflect this variability, we have revised the sentence (lines 429-431) to read: “**the study demonstrated that many PPA-based models delay thinning until the light environment is fully saturated**.”*

Q11**.** Line 499 “PPA cannot sustain this recruitment layer”. As the question asked before. I don’t know what a “recruitment layer” is. Is it a layer of first year seedlings? They don’t have to cover the whole land surface.

Reply: Yes, the recruitment layer is small tree cohorts with a DBH smaller than 15 cm.

Q12**.** “Conclusions”
I think this section summarizes the major results well. So, the abstract needs an update.

Reply: To account for the updated conclusion we have updated the last paragraph of the abstract (line 23-26).

Reviewer #3

Dear Reviewer,

We would like to thank you for your interest in our work, and for providing valuable comments that will significantly improve the quality of our publication. Below we provide a point-by-point reply to your comments, formatted in italic. Additions to the manuscript are formatted in bold italic and line references refer to the updated version of our manuscript.

Best regards,
On behalf of all authors,

Jette Elena Stoebke and David Wårlind

Comment on "Representing canopy structure dynamics within the LPJ-GUESS dynamic global vegetation model (revision 13221)" by Stoebke et al., Geoscientific Model Development

This article illustrated a good practice on introducing a new scheme of canopy structure in a vegetation demography model (VDM), LPJ, to improve the simulation of understory vegetation dynamics and plant co-existence for closed-canopy forest. I checked comments of two other reviewers and partly agree on the limitation they pointed out. However, unlike land surface models which have relatively consistent parameterizations, VDMs can vary substantially. Some of VDMs, e.g. FATES can successfully simulate understory dynamics for closed-canopy forest by introducing parameters to allow gap formation under perfect-plasticity approximation (PPA), which is also mentioned by authors in line 190. Thus, it is not an easy task to introduce a new scheme/approximation that has explicit spatial information and can be commonly applied in VDMs, and the author's scheme seems to be very specific for LPJ. As GMD require "sufficiently substantial advance in modelling science", in my opinion, the keys to judge if the merit of this paper is "sufficient" are 1) to check if the new scheme has successfully provided an alternative to height-structured light competition in closed canopy forest and 2) the new scheme improved the results of an existing mainstream VDM. This manuscript successfully evaluated the performance of the new scheme and improved a mainstream VDM, LPJ, thus is qualified to be published in GMD. I provide some suggestions below and authors shall address my concerns before this manuscript can be accepted.

Q1**.** Line 55: "internal dynamics and external drivers" What are internal dynamics specifically?

*Reply: Internal dynamics describe processes that happen within a population (self-driven processes) such as establishment, growth, and mortality. The respective examples are added to the manuscript (line 58-59). "**By resolving demographic processes, VDMs can represent how plant populations respond to internal dynamics (e.g. establishment,***

growth, mortality) and external drivers such as climate change, land-use change, management or natural disturbances. *"*

Q2**.** Line 76: "the stochastic nature of ecological processes" do you mean your model represents stochastic processes, i.e., use a random number generator in some of the processes? Is your model still deterministic?

Reply: The model is deterministic in its overall structure, but it includes specific processes that are implemented stochastically. In practice, the main model equations follow a deterministic framework, while selected ecological processes, such as establishment and mortality, use random draws to represent their inherently stochastic nature. Thus, the model is not fully deterministic, but rather a deterministic model with embedded stochastic components.

Q3**.** Line 99: "Pacala and Deutschman (1995) demonstrated that mean-field models, i.e. models which often ignore horizontal heterogeneity within a patch, can underestimate basal area by as much as 50% compared to models that account for spatial variability," This reference is quite old. I believe one of the motivations of PPA is to resolve this issue, and it partly did. So I suggest being more conservative in highlighting the importance of "spatially explicit". Trade-offs exist in VDMs, thus none of the models can be completely "spatially explicit" like individual based models, so does your SEC scheme.

*Reply: To make sure that it is clear that this approach isn't completely spatially explicit we have added the following sentence "**This approach represented an intermediate level of spatial complexity, bridging the gap between the standard non-spatial scheme and fully spatially explicit individual-based models while remaining computationally efficient**." to lines 160-162.*

Q4**.** Fig. 1: Based on the description of your scheme, that "cohorts have fixed positions within the patch", I feel it to be important for explicit/informed positions when treating recruitment. Individual based models (landis, iland, etc.) usually provide kernel function with parameters to describe the probability of seed dispersed to the neighboring area around old trees. In your SEC scheme, since the relative position information is introduced, the recruitment scheme shall also be different from other schemes, which need sort of location and distance information for determining how far the seedling is from old cohorts? Please add a description of recruitment in your SEC scheme.

Reply: In LPJ-GUESS, patches are relatively small (0.1 ha, line 151), and seed dispersal is assumed to occur uniformly within each patch. Even in the SEC scheme, cohorts do not have spatially explicit dispersal distances, and recruitment is not linked to the distance from existing cohorts. Instead, seeds are assumed to be able to reach any location within the patch with equal probability. The germination probability of the seed is then determined from the forest floor condition that varies spatially (line 171-176).

Q5**.** Line 202: For SEC and PPA, how disturbance is simulated that can be equivalent to "the patch-destroying disturbance" with a mean return interval of 100 years represented in LPD? Another question is how patch dynamics are represented after disturbance in your PPA/SEC schemes. Are both PPA and SEC schemes using "patch-since-disturbance" concept that generate new empty patch or patch with certain amount of degraded cohorts residing, similar to ED model, or they use a fixed patch setting, similar to the original PPA work by Purves et a., 2008, and the plant reaching certain canopy level through promotion and disturbance only demote certain fraction of plants and form gap? If these details are not introduced, readers will have a hard time interpreting some of your results, e.g., Fig. 9.

*Reply: The number of patches is stated in line 221: "… we used 100 replicate patches.". This applies to all canopy structure schemes used in our study and remains constant throughout the simulations. We have revised the manuscript text to make this point explicit. The updated sentence now reads: "**Across all canopy structure schemes and for the full duration of the simulations, we used 100 replicate patches. The only exception was a sensitivity analysis in which the number of patches was varied**."*

Q6**.** Line 204: During this spin-up phase, do you prescribe the initial PFT composition and stem density under different size classes using site census, or just initialize from zero with all PFT activated and provide the same amount of initial mass of seeds/seedlings to allow competition? If all PFTs are allowed to be triggered, did you check the PFT fraction after reaching equilibrium?

*Reply: LPJ-GUESS was spun up from bare ground, allowing all PFTs to establish under favourable conditions, and run until equilibrium was reached. The scenario was then initialized with a patch-destroying disturbance (lines 214-220), effectively resetting vegetation to bare ground conditions. Consequently, it was primarily important that soil conditions had equilibrated during spin-up, which requires vegetation composition to also reach equilibrium. Because the scenario begins from bare ground, the pre-scenario PFT composition was not analysed. To clarify this, we have revised the sentence in lines 214-217 to read: "**The model simulations were driven by the CRUNCEP global reanalysis climate dataset version 7 (Viovy, 2016), using a 30-year de-trended historical climatology from 1971 to 2000 to establish an equilibrium soil and vegetation condition over a 500-year spin-up period starting from bare ground and equal weighting between individuals of viable PFTs."***

Q7**.** Line 261: Did you roll back to trended climate forcings during the final "transient" simulation period before getting the "final simulation year", for a more consistent comparison to the observation?

Reply: As described in lines 214-216, we did not roll back to trended climate forcing but instead used a 30-year de-trended historical climatology (1971-2000). We assume that this de-trended climatology represents the climatic conditions around the time the observational data were collected, providing a consistent basis for comparison. A simulation period with transient climate would have potentially confounded the signal of the successional sequences resulting from the internal dynamics of the system alone.

Q8**.** Line 288: I guess all 4 schemes you used are based on a large set of shared parameters and a small set of parameters that are scheme dependent. Did you perform certain calibration for, at least, shared parameters in this study? Clarify this point in your experiment design section.

*Reply: This point is addressed in the Discussion section of our manuscript. In lines 435-436 we note: "Still, a reparameterisation of LPJ-GUESS using the new canopy structure schemes is necessary to further enhance the model's ability to align with observational data.". To this sentence we have added "**at particular sites or in global application**" to the end. Additionally, lines 535-537 state: "It is also worth noting that individual calibrations for each canopy scheme had not been performed prior to this study. Since LPD is the standard canopy scheme for LPJ-GUESS, it has undergone extensive calibration over the years." To improve clarity, we added a short statement to the model simulations section (lines 213-214), highlighting that the shared parameter set was used without additional calibration for the new canopy schemes: "**For all schemes, we applied the standard LPJ-GUESS parameterisation without performing any additional scheme-specific calibration**."*

Q9**.** Line 408: "In contrast, SEC represented a mixture of size classes and allows for the formation of canopy gaps independent of the total amount of crown area," Canopy gap is dependent of crown area for mature/closed forest with pre-defined number of canopy layers, i.e., when canopy occupied 100% the space on every layer. Thus, I'm not sure how you treat the number of layers in the SEC scheme? How many canopy layers are defined, or maybe it is a flexible number that depends on the actual recruitment and growth rate? If so, how did you bin plants into different canopy layers based on height?

Reply: In SEC, canopy layers are not defined based on the assumption that a new layer is created when total crown area fully occupies the patch. Instead, the canopy is divided into unique vertical sections (Fig. 1b; lines 166-168), within which layers are defined based on how individual cohorts intersect (Fig. 1a and its caption). The conceptual design of SEC is that cohorts have fixed positions, they cannot be rearranged to perfectly occupy the full area of the patch.

Q10**.** Line 459: "PPA's forest composition is characterised by a high proportion of shade-intolerant PFTs". A similar experiment reported by Koven et al., 2020 (Fig,.15f) shows completely opposite conclusion. This is an interesting result that may suggest different model structure/parameters to lead to completely opposite conclusions, even using the same PPA scheme. For FATES as an example, canopy layers are composed of up to 30 leaf layers for calculating absorbed PAR, and allows a portion of PAR to reach understory, even for closed-canopy forest. Thus, I can understand a different conclusion from LPJ simulation, if PAR is completely intercepted by the canopy layer when there's no gap? Please clarify.

Reply: We provide a detailed description of how our implementation of the PPA scheme differs from other implementations in the model description section (lines 186-210). In particular, we do not define canopy layers in the same way as standard PPA schemes, nor do we include any gap fraction representing small gaps between trees within a canopy layer. Consequently, when the total crown area exceeds the patch area, no gaps remain in the canopy, and light conditions at the forest floor are not favourable for the establishment of shade-intolerant PFTs (lines 421-423). In our implementation of PPA, the tallest cohorts are assigned to the patch until their cumulative crown area equals or exceeds the patch area, at which point a new understory layer is formed from the next tallest cohorts. Because shade-intolerant PFTs typically grow taller more rapidly than shade-tolerant PFTs, they tend to consistently occupy the upper canopy layer, resulting in minimal disturbance and a PFT composition characterised by a high proportion of shade-intolerant species (lines 474-479).

*To clarify the difference in our PPA implementation to e.g. FATES we have added this sentence to lines 197-199 "***This allowance for cohorts to occupy overlapping vertical space across canopy layers represents a key distinction from other implementations of the PPA framework (e.g. FATES; Fisher et al. 2015), in which cohorts from different canopy layers cannot intersect or interact.***".*