Re: “Interactive comment on ‘Effects of vegetation structure on biomass accumulation in a Balanced Optimality Structure Vegetation Model (BOSVM v1.0)’, Anonymous Referee #2”

Z. Yin, S. C. Dekker, B. J. J. M. van den Hurk, H. A. Dijkstra

1. “This is in principle a very interesting manuscript. It describes a new modeling approach to terrestrial vegetation which deals explicitly with vegetation structure and adaptation although in a simplified way. The manuscript provides the model description and the sensitivity to two model parameters, and the source code of the model is available in the supplementary information.”
A: Thanks a lot for your interesting and positive comments on the manuscript.

2. “My major concerns about the manuscript are that (i) its objective is not clearly formulated. For a manuscript submitted to GMD, I would expect that the objective of this manuscript would be something like “formulating a vegetation model which considers the effects of spatial structure and adaptation”.”
A: Thanks for your suggestion. In this study, we want to address two questions: (1) understanding the effects of vegetation spatial structure on biomass dynamics via interactions in the carbon-water-energy cycles; (2) creating a new vegetation model including vegetation structure and closing carbon-water-energy balances, which is also prepared for further study of vegetation-land-atmosphere interactions. The objective will be revised as: “In this study, our primary objective is to formulate a new vegetation model that considers effects of spatial structure and adaption to local climate via interactions with carbon-water-energy cycles. Meanwhile the new model must be easily linked to existing climate model for further vegetation-land-atmosphere interaction studies.

To approach the objective, a new coupled carbon-water-energy balance model (Balanced Optimality Structure Vegetation Model BOSVM) is developed from existing model components....” See also Referee #1, comment 6.

3. “(ii)It contains no attempt to test the model against observations even though this should be relatively easy to do as it predicts properties that are easily accessible. ... To evaluate if this objective is achieved, one would need to see that the model does a reasonable job in reproducing observations, which is currently lacking (point ii from above, rather critical!).”

A: As our study focuses on vegetation structure, we need vegetation structure observations (e.g. f_c, LAI or C_{veg}) in a large spatial scale for validation. However, there are large uncertainties and debates about the use of different available datasets, making it not trivial to compare model outputs with observations. For instance, AfSIS (http://www.africasoils.net/node/343) provides a satellite-retrieved LAI dataset, but the retrieved LAI is a mixture of grasses and woody plants, which is not suitable for validation. Baccini et al. [2008] provided the first map of above ground biomass of woody plants in Africa. However, this dataset is not sufficient for validation as we have the shoot-total biomass ratio (α) in BOSVM, which requires observed total biomass. In a forthcoming paper (published in ESDD, doi:10.5194/esdd-5-83-2014), we used the above ground biomass dataset and woody cover dataset [Hansen et al., 2003] to retrieve observed canopy structure to validate our model, where we found our results matching observations very well. This ESDD study also show transient runs of our model. As can be found in the ESDD paper, simple validation schemes are not easy due to for instance the possible bimodal behavior.
For equilibrium states and comparison to data, we decided to add a comparison between simulated and observed woody cover [Hansen et al., 2003, Sankaran et al., 2005] and a new figure in the present paper as well. Here is the paragraph that will be added to result section. Other sections will be revised based on the discussion here. "Our result is validated against observed woody cover data [Hansen et al., 2003, Sankaran et al., 2005]. In situ measurements of woody cover [Sankaran et al., 2005] are collected from several sites across Africa. The MODIS woody cover product [Hansen et al., 2003] provides a yearly satellite-retrieved tree fraction based on a regression tree algorithm. Here we use a subsample of the MODIS woody cover data developed by Hirota et al. [2011] for validation. For validation, we assumed a shoot-total biomass ratio $\alpha = 0.4$, as woody plants with $\alpha = 0.4$ can easier survive with horizontal structures (Fig. 9a). Then we chose ten vegetation canopy structures (D varies from 0.2 to 10) and simulated the equilibrium tree cover in the research region (rectangle in Fig. 5).

Figure 11 illustrates the simulated and observed woody cover as a function of mean annual precipitation (MAP). Black and grey solid circles are observed tree cover from Hirota et al. [2011], Sankaran et al. [2005] respectively. Other colored symbols are simulated equilibrium woody cover with different vegetation canopy structures for the research area. The maximum simulated and observed woody cover increase with MAP. The minimum MAP for tree survival, which is found from both observed and simulated results, is around $100\text{mm}\,\text{yr}^{-1}$). However, data from Sankaran et al. [2005] illustrates that the maximum woody cover increases until MAP=$700\text{mm}\,\text{yr}^{-1}$, while both our results and data from Hirota et al. [2011] show that the increasing trend lasts until MAP=$900\text{mm}\,\text{yr}^{-1}$. When MAP>1000 $\text{mm}\,\text{yr}^{-1}$ the maximum woody cover from simulation maintains at 0.9, which is overestimated (0.8 from observations). However, we also need to realize that data from Hirota et al. [2011] are derived from satellite images.

Effects of vegetation structure on simulated equilibrium woody cover are clearly shown in Fig. 11. Vertical structure (high D values) is easier to survive under arid climate. With increase of MAP, the equilibrium woody cover of vertical trees grows very slow. In contrast, trees with a horizontal structure hardly survive when MAP is low. However, once MAP is sufficient for their survival, they can produce a higher equilibrium cover than vertical trees."

In the Discussion section, we will add: "Our model is validated by observed woody cover datasets from Sankaran et al. [2005], Hirota et al. [2011]. Results showed that the BOSVM successfully predicted the threshold of MAP (100 $\mathrm{mm\,yr^{-1}}$) for trees survival. Our results also showed that maximum woody cover increase with the increase of MAP till 1000 $\mathrm{mm\,yr^{-1}}$, which is consistent with Hirota's dataset. Moreover, by considering the variety of vegetation structure, the BOSVM model is able to interpret the large variance of observed woody cover under wet climate."

4. "(iii)I get no sense for how sensitive the model is to its parameters, given that the model contains a large number of parameters with inherent uncertainties and assumptions regarding functional relationships."
A: Our main aim is to investigate the effects of vegetation spatial structure on biomass dynamics. Thus we only focus on two structural parameters (α and D) in the sensitivity analysis. The BOSVM indeed contains numerous parameters, but its parameterization is based on existed models (e.g., LPJ [Sitch et al., 2003], TRIFFID [Cox, 2001], CTESSEL [Boussetta et al., 2013], TESSEL [van den Hurk et al., 2000]), which are used in different early system models . To illustrate the sensitivity of the model to all its parameters is beyond the scope of this paper.
In this study, we focus on vegetation spatial structure, which is described by two free parameters (α and D). To test the sensitivity of BOSVM to these two parameters, we vary α and D in a reasonable range and simulate vegetation growth under same climates. Results are shown in Fig.7–9. Through this approach, we illustrate the sensitivity of the model to these two parameters. Indeed, α and D do have impacts on other variables and other parameters can influence these impacts, but these details are not where our interest is. Moreover, these complicated interactions and inherent uncertainties finally distribute to vegetation biomass, which already is included in our sensitivity analysis.

5. "(iv)There is no critical discussion of the main limitations of the model."
A: The limitations of the BOSVM model will be added in the discussion, also based on comments by Referee #1 as: "As our interest is effects of vegetation structure on their total biomass with given climate regime, numerous factors that may significantly influence biomass dynamics are not taken into account. Dardel et al. [2014] found that soil type is an important driver of vegetation-climate interactions. The property of soil determines soil water holding capacity, which in turn affects soil water balance. Grass-tree competition may limits the potential maximum biomass of grasses and woody plants, which is lack of this study. Grasses prohibit the colonization rate of woody plants and provide fuel for fire occurrence [Staver et al., 2011], which further limit the biomass of

woody plants. Moreover, human activities [Kleidon, 2006] and topography [Klausmeier, 1999] have potential effects on dynamics of the ecosystem under certain climate regime, which are not considered in this work."

6. "Adaptation is (presumably) dealt with in the manuscript with the maximization approach, but this has not been made quite clear and it is not being discussed in the discussion and this aspect lacks completely in the conclusions. Since objectives and conclusions are rather important parts of a manuscript, these need to be sharpened in the revision."
A: In introduction section, we will revise as: "To understand how vegetation adapt to its local climate by changing its spatial structure, an optimization approach is applied by assuming that vegetation tries to maximize its total biomass [Schymanski et al., 2010]. Over the past decades, numerous objective functions were proposed to explain the universal principle of vegetation adjustment to climate, such as maximizing water use efficiency [Schymanski et al., 2008], maximizing net carbon profit [Schymanski et al., 2007, Dekker et al., 2010] or minimizing soil water stress [Rodriguez-Iturbe et al., 1999]. However, Schymanski et al. [2010] found that the maximizing total biomass is in principle equal to maximum entropy production, which is a universal objective function for ecosystem dynamics in the carbon-energy-water cycles [Dewar, 2003, Kleidon, 2004, Kleidon and Schymanski, 2008]. Through the maximization process, we will show how optimal vegetation structure (maximizing total biomass) shifts with the change of climate regime by carbon allocation and strategies to drought. By understanding the mechanism that leads to a shift of the optimal structure, we can enhance the prediction of phenology change with climate."

In discussion section 4.1, we will add: "Moreover, our results show that the optimization approach (maximizing the total biomass) successfully explains why patchy vegetation is optimal under arid and semi-arid conditions (Fig. 7–9), which was also found by Schymanski et al. [2010]. In contrast to a homogeneous distribution (horizontal structure), vegetation patches (vertical structure) have higher water use efficiency, which is important to biomass production under water limited conditions."

In conclusion, we will add: "An optimization approach (maximizing total biomass) is applied to investigate how vegetation adapts to local climate via optimizing spatial structure, which can explain why patches are optimal under arid and semi-arid conditions. We found that the optimal vegetation structure shifts with climate. ..."

7. "I am also confused about the maximization approach. Throughout the manuscript, the authors refer to maximized water use efficiency, fractional cover, biomass and carbon gain. These aspects are clearly related, as shown in Fig. 3, but it appears the authors only deal with maximizing biomass. In the revision, it is important to clarify which aspects are maximized (i.e., the goal function) and which variables are optimized (i.e. values that are associated with the maximization of the goal function)."

A: In the introduction, we reviewed literature about optimization approaches, from where we found that maximizing total biomass may be a reasonable and universal principle in ecosystems. Thus in this study, we only optimize vegetation structure (α and D) via maximizing total biomass (the goal function). In Fig. 3, we present the relation between vegetation structure and GPP, R_{WU} and WUE to explain the mechanism by which vegetation structure can affects the total biomass (see reply to comment 6). Thus, in this study only total biomass (C_{veg}) is maximized. α and D are optimized. Also see reply to comment 6 and 10. We will clarify this in the new manuscript.

8. "Also, it would be really helpful to already describe the relationships (Fig. 3) in the introduction because it is central to the formulation of the model."
A: Thanks for your suggestion. Fig. 3 shows the main mechanism how vegetation structure affects biomass via GPP, water use efficiency and relative water use. However, since this figure is based on the parameterization and the proposed mechanisms of BOSVM introduced in Section 2, we think it's better to keep Fig. 3 after the model description.

9. "Why did the authors chose to maximize biomass rather than NPP or carbon profit? Are these attributes related in the model output?"
A: Schymanski et al. [2010] found that maximizing biomass is equal to maximizing entropy production, which is a universal objective function for ecosystem dynamics. We will discuss the optimization approach in the introduction (see reply to comment 6).

10. "An overview at the beginning of the methods section would be very helpful that describes the main state variables of the model, the goal function, and the parameters that are being optimized."
A: True. However, the overview (the goal function and optimized parameters) is based on the BOSVM model. Thus we think it's better to introduce the goal function after introducing the BOSVM model. In section 2.7, we will add: "In this study, we try to understand how vegetation adapts to climate via optimizing its spatial structure (α and D). We assume that the objective of the adaption is that vegetation tries to maximize its total biomass, which is the goal function:

$$\mathrm{Max}(C_{\mathrm{veg}}) = f(\alpha, D)$$

To maximize the total biomass, vegetation structure parameters (α and D) need to be optimized. Nevertheless α and D cannot influence C_{veg} directly, but determine C_{veg} via numerous mediate variables in the carbon-water-energy cycles."

11. "It would be very helpful if the variables in the equations are single letters, and use subscripts to differentiate these. At present, some variables, e.g. C A, look like the product of two variables, C and A."
A: Some special symbols (e.g. LAI, PAR, NPP, GPP, etc) are widely used in this research area (see for instance [van den Hurk et al., 2000], [Sitch et al., 2003] and [Boussetta et al., 2013]). So we think we'd better keep them. However, we will make letters of multi-capital

variables more tight (e.g. $L\,A\,I \rightarrow LAI$) and add “·” to where multiplication occurs.

12. “The description of the surface energy balance in the appendix uses different symbols for the same fluxes, which is confusing. Please use the same symbols throughout the whole manuscript!”
A:Corrected.

13. “Eqn A1 is referred to before it is explained. Also, a reference is made to Appendix A in Appendix A, which is rather strange.”
A: Equation A1 will be moved before where it is referred.

14. “Note that “effect” is a noun, while the verb is “affect” (in most cases). There are a couple of places in the manuscript where this is misspelled.”
A:Corrected.

Bibliography

A. Baccini, N. Laporte, S. J. Goetz, M. Sun, and H. Dong. A first map of tropical Africa's above-ground biomass derived from satellite imagery. *Environmental Research Letters*, 3(4):045011, 2008.

S. Boussetta, G. Balsamo, A. Beljaars, A. Panareda, J. C. Calvet, C. Jacobs, B. J. J. M. van den Hurk, P. Viterbo, S. Lafont, E. Dutra, L. Jarlan, M. Balzarolo, D. Papale, and G. van der Werf. Natural land carbon dioxide exchanges in the ECMWF integrated forecasting system: Implementation and offline validation. *Journal of Geophysical Research: Atmospheres*, 118(12):5923–5946, 2013. ISSN 2169-8996. doi: 10.1002/jgrd.50488. URL http://dx.doi.org/10.1002/jgrd.50488.

P. M. Cox. Description of the “TRIFFID” Dynamic Global Vegetation Modeltion model. Technical report, Met Office, 2001.

C. Dardel, L. Kergoat, P. Hiernaux, E. Mougin, M. Grippa, and C. J. Tucker. Re-greening sahel: 30 years of remote sensing data and field observations (mali, niger). *Remote Sensing of Environment*, 140(0):350–364, 1 2014. doi: http://dx.doi.org/10.1016/j.rse.2013.09.011. URL http://www.sciencedirect.com/science/article/pii/S0034425713003325.

S.C. Dekker, HJ De Boer, V. Brovkin, K. Fraedrich, MJ Wassen, and MG Rietkerk. Biogeophysical feedbacks trigger shifts in the modelled vegetation-atmosphere system at multiple scales. *Biogeosciences*, 7(4):1237–1245, 2010.

Roderick Dewar. Information theory explanation of the fluctuation theorem, maximum entropy production and self-organized criticality in non-equilibrium stationary states. *Journal of Physics A: Mathematical and General*, 36(3):631, 2003. URL http://stacks.iop.org/0305-4470/36/i=3/a=303.

M. C. Hansen, R. S. DeFries, J. R. G. Townshend, M. Carroll, C. Dimiceli, and R. A. Sohlberg. Global percent tree cover at a spatial resolution of 500 meters: First results of the MODIS vegetation continuous fields algorithm. *Earth Interactions*, 7(10):1–15, 2003.

M. Hirota, M. Holmgren, E. H. Van Nes, and M. Scheffer. Global resilience of tropical forest and savanna to critical transitions. *Science*, 334(6053):232–235, 2011.

C.A. Klausmeier. Regular and irregular patterns in semiarid vegetation. *Science*, 284 (5421):1826–1828, 1999.

A. Kleidon. Optimized stomatal conductance of vegetated land surfaces and its effects on simulated productivity and climate. *Geophys. Res. Lett*, 31:L21203, 2004.

A. Kleidon. The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization. *Global and Planetary Change*, 54(1):109–127, 2006.

A. Kleidon and S. Schymanski. Thermodynamics and optimality of the water budget on land: a review. *Geophysical Research Letters*, 35(20):L20404, 2008.

I. Rodriguez-Iturbe, P. D'odorico, A. Porporato, and L. Ridolfi. On the spatial and temporal links between vegetation, climate, and soil moisture. *Water Resources Research*, 35(12):3709–3722, 1999.

M. Sankaran, N. P. Hanan, R. J. Scholes, J. Ratnam, D. J. Augustine, B. S. Cade, J. Gignoux, S. I. Higgins, X. Le Roux, F. Ludwig, J. Ardo, F. Banyikwa, A. Bronn, G. Bucini, K. K. Caylor, M. B. Coughenour, A. Diouf, W. Ekaya, C. J. Feral, E. C. February, P. G. H. Frost, P. Hiernaux, H. Hrabar, K. L. Metzger, H. H. T. Prins, S. Ringrose, W. Sea, J. Tews, J. Worden, and N. Zambatis. Determinants of woody cover in African savannas. *Nature*, 438(7069):846–849, 2005.

S.J. Schymanski, M.L. Roderick, M. Sivapalan, L.B. Hutley, and J. Beringer. A test of the optimality approach to modelling canopy properties and co_2 uptake by natural vegetation. *Plant, Cell & Environment*, 30(12):1586–1598, 2007.

S.J. Schymanski, M.L. Roderick, M. Sivapalan, L.B. Hutley, and J. Beringer. A canopy-scale test of the optimal water-use hypothesis. *Plant, Cell & Environment*, 31(1): 97–111, 2008.

Stanislaus J Schymanski, Axel Kleidon, Marc Stieglitz, and Jatin Narula. Maximum entropy production allows a simple representation of heterogeneity in semiarid ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365 (1545):1449–1455, 2010.

S. Sitch, B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky.

Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the lpj dynamic global vegetation model. *Global Change Biology*, 9(2):161–185, 2003. doi: 10.1046/j.1365-2486.2003.00569.x. URL `http://dx.doi.org/10.1046/j.1365-2486.2003.00569.x`.

A. C. Staver, S. Archibald, and S. A. Levin. The global extent and determinants of savanna and forest as alternative biome states. *Science*, 334(6053):230–232, 2011.

B. J. J. M. van den Hurk, P. Viterbo, A. C. M. Beljaars, and A. K. Betts. *Offline validation of the ERA40 surface scheme*. European Centre for Medium-Range Weather Forecasts, 2000.

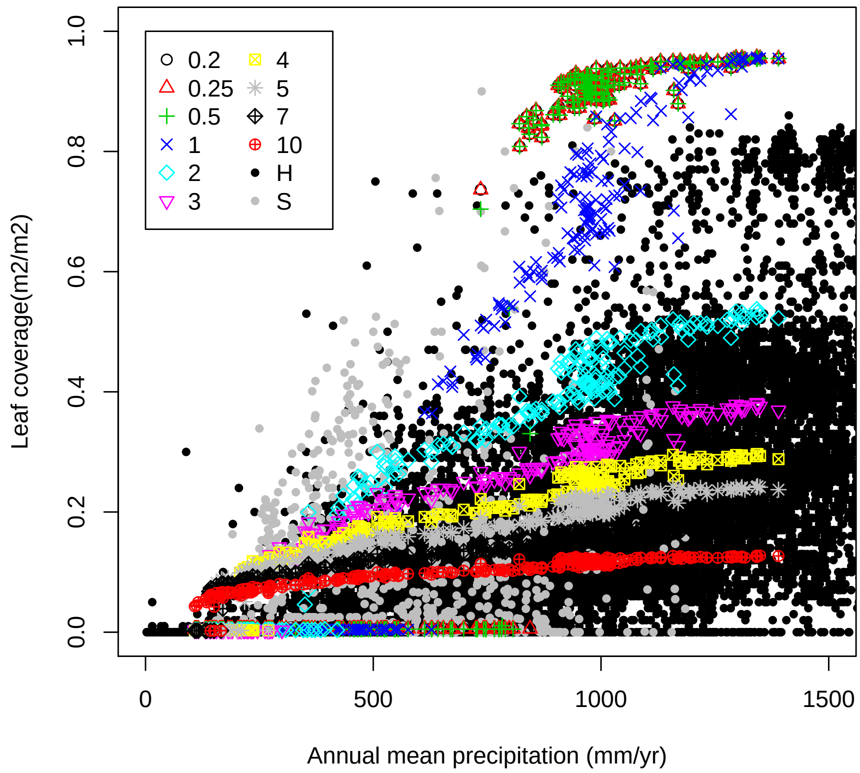

Figure 11: Simulated and observed woody cover as a function of mean annual precipitation. Black and grey solid circles are observed tree fraction from Hirota et al. [2011], Sankaran et al. [2005] respectively. Other symbols indicate simulated equilibrium woody cover with specific canopy structure in the study region (rectangle in Figure 5). Related D values are shown in the legend. The shoot-total biomass ratio α is fixed as 0.4.