Reply to Anonymous Referee #2

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

1. "I find the most interesting argument is that detection of multi-modality of tree cover is largely dependent on solar radiation and aboveground biomass (as a central message conveyed by the title). This would imply -though the authors did not make such corollary explicitly- that the distinct ecosystem states (i.e., treeless, savanna and forest) could be simply caused by the discontinuously distributed environmental/ecological factors, and therefore the alternative stable states theory is not necessarily invoked to explain the observed pattern in the tropics. In this sense, this paper has merits that call attention to a more comprehensive set of environmental/ecological variables when it comes to analysing frequency distribution of ecosystem states."
   A: Thank you for your comments. In this paper we do show that the mode of tree cover can be partly determined by solar radiation and above ground biomass, but it does not mean that the bifurcation theory is not important to explain the bimodal distribution of woody cover in West Africa. We regret that the discussion in the previous manuscript is not clear and probably resulting in this misunderstanding. Indeed bimodality does not directly mean bistability. For instance bimodality can occur due to discontinuous distributed environmental factors. However, in our case we have strong feedbacks between the climate and its vegetation as also mentioned by the reviewer under question 2. So a bimodal distribution in climate could be caused by the bistable behaviour of the coupled system and vice versa. We have improved the discussion. Please check our reply to the second question below.

2. "However, the basic logic here is questionable: for their analyses the authors merely consider radiation and biomass as potential 'drivers' or 'conditions' of existence of bi-stable tree cover (e.g. Table 2. 'woody cover states determined by radiation and biomass states'). However, the bimodal distribution of these variables is plausibly dependent on bimodal tree cover as well. In fact, there are important feedbacks between these state variables (the authors mentioned such kind of feedbacks in the Introduction as well). For instance, rainforests having high tree cover can substantially modify regional radiation regime (e.g., through producing more clouds), compared with savanna and treeless states. In this sense, we may expect bimodality of radiation is (at least partly) a result of bimodality of tree cover. Indeed, there are complex feedbacks between these factors that make it difficult to disentangle their relationships, but the authors need to explicitly acknowledge the feedbacks, and elaborate their logic in the Introduction and other relevant places."

A: True. Radiation and biomass are strongly coupled with woody cover. And the interactions among them are complex. In fact the motivation of this paper is from the observed bimodality of woody cover and the strong vegetation-climate interactions in West Africa. If alternative stable states exist and vegetation strongly interacts with its local climate, bimodality should also exist in some climatic variables which are highly integrated in the loop of vegetation-climate interactions. Here we chose the mean annual incoming shortwave radiation as a measure of the vegetation-climate interactions. Moreover, the two modes of the specific climatic variable should be equal to the corresponding two modes in the woody cover. That is: all samples from one mode of the radiation (say low radiation) should belong to the corresponding mode of woody cover (high woody cover). Thus we designed the conditional histogram analysis. Details are discussed in the Discussion section of the new revised manuscript. Especially in one paragraph we underline that:
" Based on the bifurcation theory, ecosystems may form alternative stable states under the same climate condition due to different feedback mechanisms. In this study, the mean annual precipitation is the general climate condition. Thus the observed bimodalities of W and B are strong evidences of alternative stable states under different $\overline{P}$ bands. However we notice that $\overline{R}$ can be an ideal measure of the strength of the vegetation-climate interactions, through which we can estimate the stability of the two W modes. And our results (in Table 2) demonstrate that unimodality of W is found under specific conditions of W and $\overline{R}$. It implies that the W state is stable under such conditions. However bimodality of W still exists under an intermediate status: low B and low $\overline{R}$, revealing where critical transitions might occur. Numerous studies tried to find early warning signals of possible critical transitions through different approaches. However they only focused on indicators from the dynamics of vegetation to estimate ecosystem states. The essential reason of most alternative stable states in ecology, feedback mechanisms, is not explicitly considered. This study uses a climatic variable $\overline{R}$ and a proxy variable of woody plants' age B to estimate the stability of vegetation states through measuring the strength of the specific feedback mechanism. This approach does not need long time series data of vegetation dynamics but only a screen shot of vegetation biomass and short time observations of a proper climatic variable. We agree that this approach does not allow the quantification of complex feedbacks between e.g., land cover and local climate, for which more complex observations and analyses are needed."

3. "In the meantime, the Discussion part needs to be improved to accommodate implications on the core findings (conditional bimodality of tree cover), especially a clear link to the previous explanation of alternative stable state theory on tropical tree cover patterns."
A: Your comments help us to improve the manuscript a lot. Thank you. The first part of the Discussion is totally rewritten following your comments. Now it clearly explains our logic, findings and conclusions.

4. “Introduction and Discussion: To facilitate broader readership, it would be better to give a brief introduction on the context of the link between frequency distribution and alternative stable states, multimodality of tree cover in the tropics, theoretical and/or practical significance, etc. Also the niche (and aim) of this study need to be elaborated: what is the general importance of this work, apart from that more climatic variables are included for detecting bistability?”
   A: Thank you. The motivation and hypothesis are added in the Introduction. Also we simply explained the link among bimodality, alternative stable states and bifurcation theory in both the Introduction and the Discussion. For the Discussion please check our reply to Question 2. One new paragraphs are added in the Introduction as:
   “We hypothesize that multimodality should not only be found in woody cover, but due to the strong climate-vegetation interaction they also should be found in some other variables, which are integrated in these feedback loops. In this paper we choose above ground biomass B (Hansen et al., 2003) and mean shortwave radiation $\overline{R}$ (Boone et al., 2009) to verify our hypothesis. The B can be seen as a proxy for the development age of woody plants. It is also an measure of the fire feedback (Mayer et al., 2011) as high fire frequency and severity can reduce woody biomass significantly and lead to low B. The $\overline{R}$ is an ideal climatic variable to estimate the strength of the cloud feedback. A small $\overline{R}$ is interpreted as an environment with a more uniformly distributed precipitation regime, where fire is rare and woody plants can extend their canopies to increase W. And high W can in turn diminish $\overline{R}$ by affecting cloud cover through reinforcing evapotranspiration (Entekhabi et al., 1992). Thus we first expect that the bimodality can also be found in both B and $\overline{R}$. Moreover, the mode of low W in the bimodality is expected to equal to that of low B and high $\overline{R}$. Vice versa.”

5. “Data: It has been suggested that the inference of multimodality from the MODIS VCF data has some caveats. A very recent paper (Xu et al. 2015. A Changing Number of Alternative States in the Boreal Biome: Reproducibility Risks of Replacing Remote Sensing Products. Plos ONE) shows that the update of this remote sensing product could have a substantial impact on the detection of multimodality. It would be ideal if the authors can re-do the analyses based on the updated version (Collection 5) of MODIS VCF data. They should at least acknowledge this caveat, if they are not able to re-do them.”
   A: True. Xu et al. (2015) show that although multimodality still exists in the new version of the VCF data set, but the histogram changes a lot for the boreal regions. As Xu et al. (2015) have showed, both products (collection 3 and 5) are highly correlated, meaning that indeed the histograms can change but not their multimodality. In next step we will extend our experience from this work to the whole tropical regions, where the two version of data sets will be carefully compared. Thus for this paper we only discussed it in the Discussion as,
   “This study simply tests the climatic approach in West Africa. In the next step, this approach will be extended to the whole tropical regions to estimate the sta-

bility of vegetation states at global scale. Recently a new version of MODIS VCF (Collection 5) is available (DiMiceli et al., 2010). Xu et al. (2015) found that the multimodality of boreal plants is still exist in the new version but the density distribution varies significantly compared with the previous version (Collection 3, Hansen et al. (2003)). Thus the difference of the two VCF version in the tropical area should be carefully investigated before analysis. Moreover, it will be of interest to test whether the two modes of W from Collection 3 are equal to that from Collection 5 by the conditional histogram."

6. "Fig. 1: the bimodality of radiation (Fig. 1e) looks not clear from the histogram (more like a unimodal distribution), can you provide results from the latent class analysis that can justify bimodal distribution as the best fit?"
   A: We illustrate the histogram of $\overline{R}$ under different $\overline{P}$ bands in Fig. R1. In most bands, the distribution shows two peaks and the threshold is approximately around 215–220 $\mathrm{W\,m^{-2}}$. The ICL of class number is shown in Fig. R2. Although three-class model is shown as the best fit, the ICL value of two classes is very low as well. Moreover, the means of the detected three classes are 184, 200 and 223 $\mathrm{W\,m^{-2}}$. From Fig. R1 we can find that the first two modes are tightly linked and the difference between them is far less than that between the second and the third mode. Thus we decided to select the two-class model and illustrate the fitted normal distributions in Fig. 1(e) in the manuscript. We mentioned this in the first paragraph of Sect. 3.1 and put the details in the online supplement.

7. "P6, lines 4-5: It is probably not a sufficient sampling size of 50 data points ($< 1\%$) for the bimodality test. Why not just use all the data points (not very heavy for computation)?"
   A: This is only for the bimodal test in the whole research area. The research area contains more than 2500 climatic grid cells (101×51 grid cells, less than half is covered by sea) and each grid cell contains 12321 samples. So we only randomly selected 50 samples from each grid cell to estimate the W distribution in the whole region. But for the bimodal test in each grid cell (as shown in Fig. 4 in the manuscript) we used all samples after filtering anthropogenic land cover. We mentioned it in the first paragraph of Section 2.3 as "For this, all vegetation cover data in every 0.5° climate grid cell (containing 12321 MODIS 500×500 m grid cells each) in this larger domain are processed, and GlobCover data points being flagged as human activities are removed."

8. "P7, lines 20-23: Why consider bimodal distributions as unimodal if one of the modes has less than 20% of the points? Why not just follow the test? In these ways you underestimate bimodality, so it shouldn't be surprising to find little climatic overlap of the different states."
   A: The bimodal test is not perfect. At least, it cannot meet all requirements in this study. If the proportion of one detected mode (by the bimodal test) is too low or too high, three types of error (see next paragraph and Figure R3 – R4) will occur, where W is actually unimodal distributed but is detected as bimodality by

the test. At the beginning we set a threshold to avoid the three types of error. But we agree that the threshold (20/80%) was too coarse. In the revised manuscript we use 5/95% as the threshold and update all related figures, tables and text.

We collect all climatic grid cells that meet the two conditions: 1) Bimodality of W is detected by the test. 2) The proportion of one detected mode is less/more than 5/95%. These grid cells can be divided into four categories. Fig. R3 shows the W distribution and fitted normal distributions of one selected grid cell from the specific category: Type I: Bimodality is detected, but the proportion of the savanna state is less than 5%. In this case, the mean of the fitted savanna state (green curve) is over 0.6. Thus we just consider it as unimodal distribution. Type II: Bimodality exists, but both of the modes belong to the treeless case. So we consider it as unimodal. Type III: It is similar to type II, but the two modes belong to the savanna state. Type VI: A special case, but this type only contains two grid cells (Fig. R4). Type I–III are the three types of error discussed above. The type IV is an exception, which only occurs twice. In Figure R4 we illustrate density distributions of all grid cells from the four types. N is the cell number of the specific category.

Figure R5 and R6 shows the difference of plots between the previous and the current version. We can find that the updated threshold does not change the main results in principle.

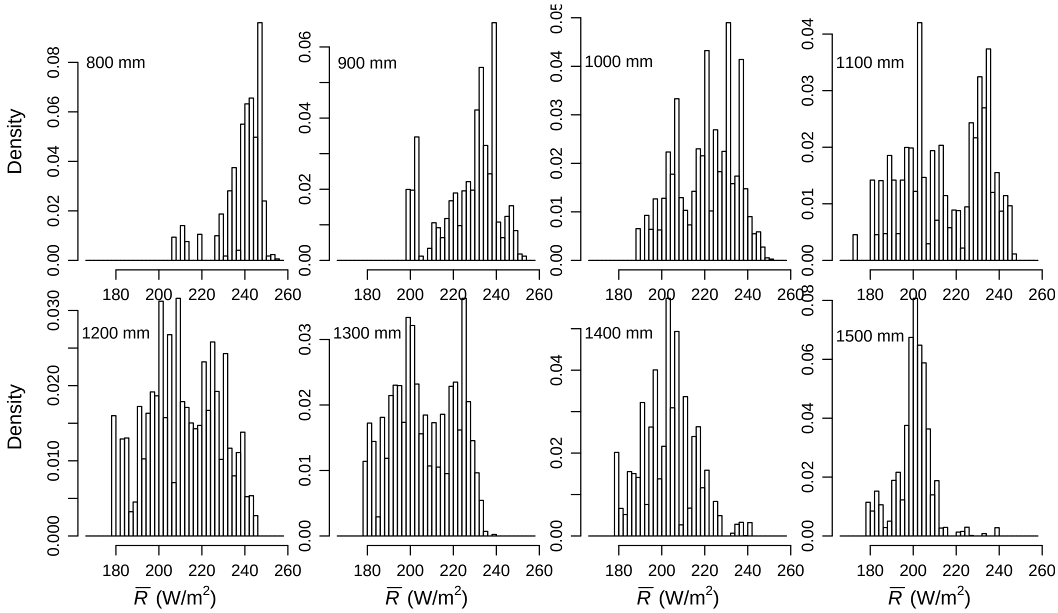

Figure R1: Density distribution of mean annual incoming shortwave radiation $\overline{R}$ under different precipitation bands.

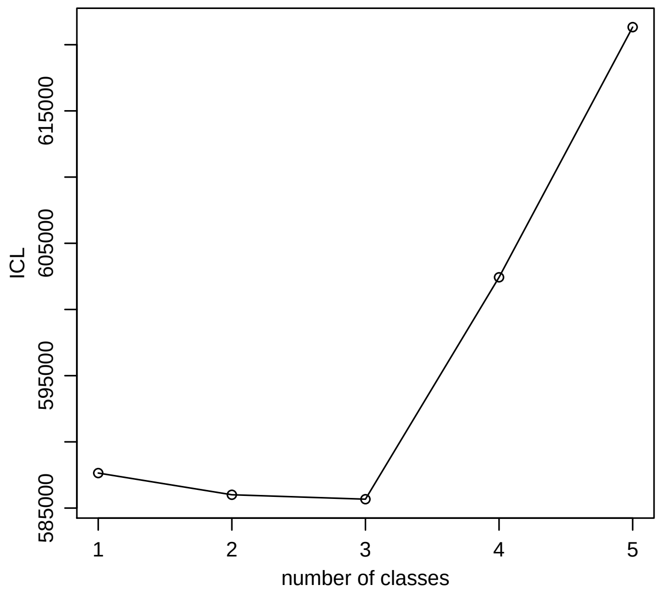

Figure R2: The Integrated Completed Likelihood (ICL) of class numbers of $\overline{R}$ in the whole research region.

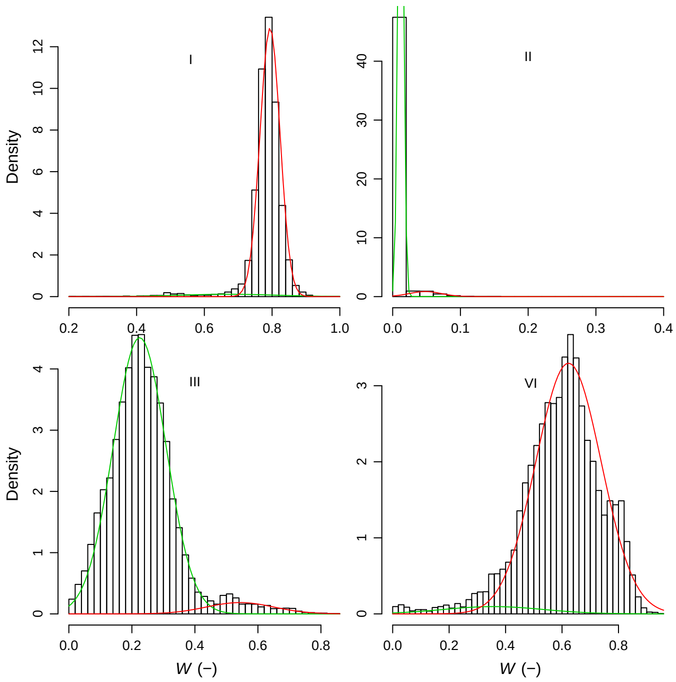

Figure R3: Four special types of W histograms that are detected as bimodal distribution. Red and green lines indicate the two normal distributions that are fitted by the bimodal test.

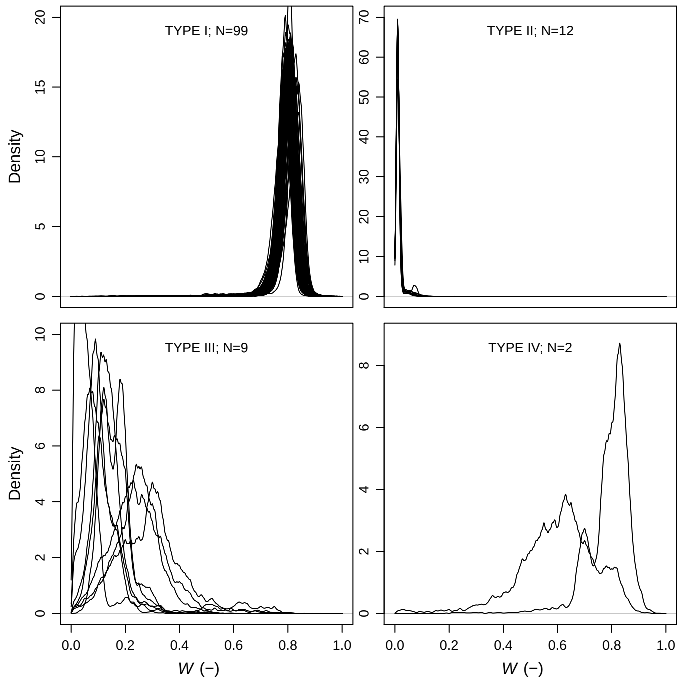

Figure R4: Histograms of W of all grid cells that belong to the four types. N is the number of grid cells in the specific category.

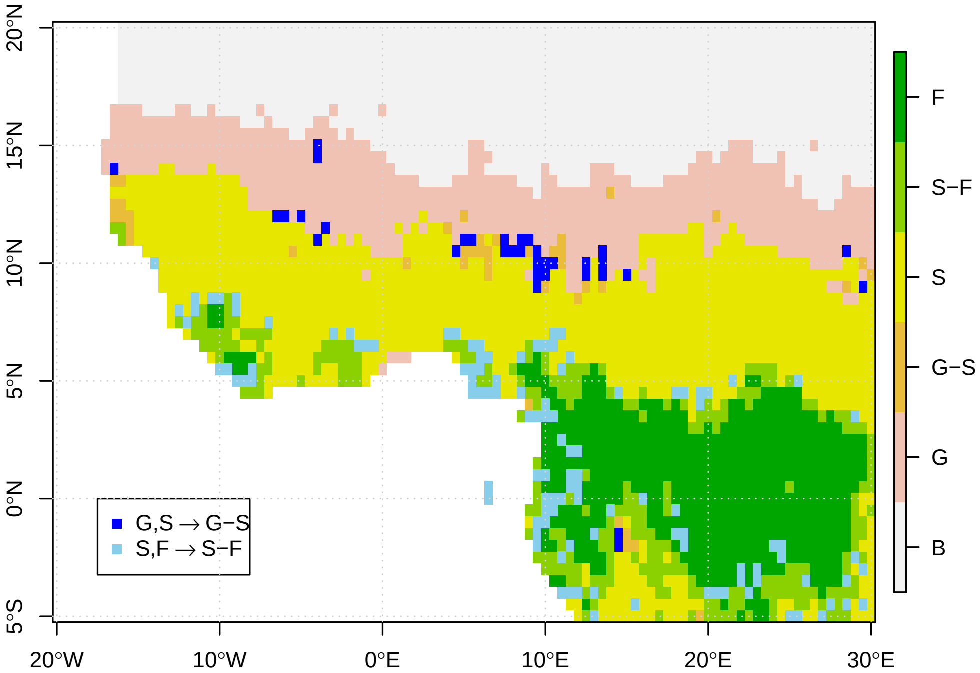

Figure R5: Comparison of land cover classification between the previous and the current version. The previous version uses 80% as the threshold to decide whether the W distribution is unimodal or bimodal. The current version uses 95%. Blue grid cells are where unimodal of grass or savanna are classified in the previous version but coexistence of grass and savanna are classified in the current version. Sky blue grid cells are where unimodal of savanna or forest are classified in the previous version but coexistence of savanna and forest are classified in the current version.

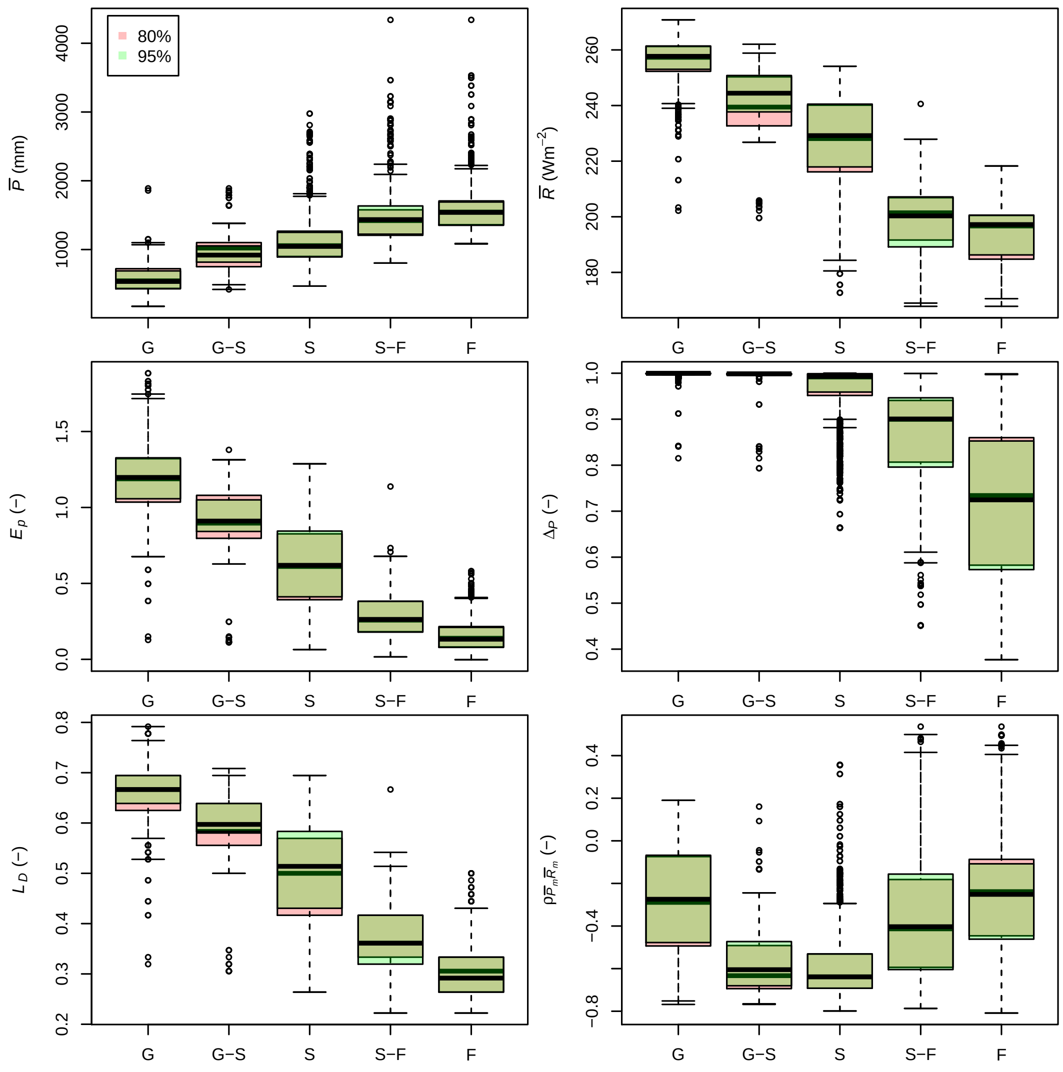

Figure R6: Boxplots of climatic indicators vs land cover types. Red color indicates boxplots in the previous version (80% as threshold). Light green color indicates boxplots in the current version (95%).