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Interactive comment on "Amazon forest structure generates diurnal and seasonal variability in light utilization" *by* D. C. Morton et al.

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Referee #3

Morton et al. use a 3D model to simulate radiation transfer in an Amazon forest canopy to demonstrate that there is diurnal and seasonal variability of canopy light utilization. The main finding suggests that light utilization is lowest during the dry season months. This result is explained as a mixture of shading and light saturation effects.

The topic of the paper is timely and relevant: understanding canopy architecture effects on the diurnal and seasonal light utilization by canopies will help to understand the current seasonal dynamics of ecosystem exchange of water, carbon and energy. Additionally, given the plethora of satellite products available at the moment, the study

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is also timely given the variability found in daily canopy utilization values.

I found the start of this paper hard to understand, with parts of the methodology not being explicit. i.e. how was light utilization and light saturation estimated? See specific lines below. Also, some parts of the text is not self explanatory, and assumes that all readers are expert in the topic. Figures are rather vaguely explained, this could improve.

Response: We have modified methods sections to clarify the details regarding the model set up and simulations, including a clarification of terminology used to describe light saturation and light utilization. Figure captions have also been expanded to provide more details on the content and interpretation of key findings (see specific comments below regarding Figure 2 and Figure 5).

Although these are modelling results, the results are presented as 'truth' with no discussion on the sensitivity of the results to the underlying assumptions. How sensitive are these results to the assumptions of: 1) Light utilization calculation 2) Assumptions of light saturation. Top canopy leaves would have much higher light saturation values than mid and low canopy levels, also these leaves should be adapted/acclimated to usual dry season irradiance levels. This ought to be accounted for at least as a sensitivity test as it might be one of the key driver of this paper results 3) Parameterisation of light absorption by woody elements and ground surface 4) Volume or area of branches simulated with DART 5) Amount of atmospheric aerosols chosen for these 1 day simulations per month. A sensitivity analysis to the above assumptions is pertinent.

Response As suggested, we have expanded our discussion of the methods, including the development of the model scene and simulation conditions. In addition, we have added material to the discussion to highlight the potential for model-data comparisons in a future study, especially if data can be collected to constrain variability in light saturation at the leaf level among species, canopy positions, and leaf ages.

New discussion paragraph: In addition to data on branch structure, new field data are needed to constrain the influence of plant trait variability on canopy reflectance and light utilization. Recent studies highlight the potential for leaf demography to alter leaf reflectance on a seasonal basis (Chavana-Bryant et al., 2016; Wu et al., 2016; Brando et al., 2010). Without a broader sample of Amazon tree species, and additional data on transmittance and absorptance, it is unclear whether subtle and short-term changes in leaf reflectance properties (Chavana-Bryant et al., 2016) are sufficient to alter PAR availability for canopy and understory trees. New data are also needed to model differences in light saturation among species, canopy positions, and leaf ages. Subsequent studies that combine forest 3D structure (including branches) with leaf-level variability in light saturation could extend the work in this paper on the contributions from shadowing and light saturation to seasonal variability in light utilization in tropical forests.

Aerosols levels in the Amazon region are known to be high during the dry season months with estimated relevant impacts of diffuse radiation effects on GPP during these months (Rap et al 2015). It would be relevant to see specific effects of diffuse radiation during these months on light utilization/LUE and how the specified value of AOD/aerosols in these simulations influence the dry season results.

Response: We used aerosol information from the Belterra AERONET station to develop our monthly climatology of AOD, and used the DART atmospheric radiative transfer module to estimate diffuse light from aerosol scattering under clear sky conditions. For clarity, we have added the monthly climatology of AOD to Table S1.

The paper suggests that these results could be an alternative explanation to the observed Amazon forest seasonality. However, lower light utilization during dry season months will necessarily mean lower photosynthetic uptake which is opposite to what the actual observations show for most forest sites in the amazon region.

Response: Our analysis investigates diurnal and seasonal variability in PAR absorption by leaves. Our findings suggest a seasonal increase in light utilization, albeit smaller than what would be estimated using measurements of incident PAR at the top of canopy

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without considering illumination geometry and forest 3D structure (see Figure 4). Fractional utilization is lowest in the dry season (counter to previous reports using eddy tower data to estimate light use efficiency or photosynthetic capacityâĂŤsee Restrepo-Coupe et al., 2013), but the combination of lower utilization and higher incident PAR still results in a seasonal increase in light available for photosynthesis.

Understanding the influence of forest structure on net primary productivity would require an ecosystem model to consider the response of photosynthesis to temperature and water stress, in addition to variability in APAR, as well as seasonal changes in heterotrophic respiration. Improving the representation of 3D forest structure in ecosystem models is an important area for future research.

Is there any possible way to validate any of these results with some observations of LAI profiles through the canopy http://www.scielo.br/pdf/aa/v35n4/v35n4a07.pdf or vertical profiles of radiation measurements, measured at one of the Tapajos towers? or with any other observations?

Response: Vertical profiles of illumination within the canopy, as estimated in the paper by Marques Filho et al. (2005), provide important insights into the integrated impact of leaf and branch material on light availability. This is a promising avenue for further work, potentially in combination with measurements of leaf and branch attributes needed to improve model parameters of reflectance, light saturation, and absorption by woody material. For example, Movie S2 illustrates estimates of illumination variability near ground that could be compared with a network of PAR sensors in the understory.

Existing measurements for other sites, either of incident PAR or plant area index, offer some context but could not be directly compared to our model results. Our model scene is derived from lidar data near the KM67 flux tower in the Tapajos National Forest. However, the Tapajos forest is the most vertically differentiated Amazon site in the Sustainable Landscapes lidar database (http://mapas.cnpm.embrapa.br/paisagenssustentaveis/), highlighting the need for co-

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located field and lidar measurements to validate the model results.

Line 26, page 19049 Light utilization, this is a key concept on this paper, for clarification purposes would be best if the equation used is added

Response: Utilization of absorbed light is constrained based on a photosynthetic light response curve from leaf-level measurements of tropical forest trees (Anacardium, Kitajima et al., 1997). The concept is illustrated in Figure 2, where the blue curve shows the percent utilization. Below 225 μmol m-2 s-1, leaves can utilize all absorbed PAR for photosynthesis. Above this threshold, fractional light utilization drops below 1, indicating a shift from light to rubisco limitation of photosynthesis.

Lines 23-24, page 19049, Light saturation effects: explain what these are and explicitly how this was accounted for. What values were used?

Response: Light saturation effects are calculated as the difference between the leaf absorption and light utilization. This concept is illustrated in Figure 2. The dashed line (light utilization) is the product of the red and blue curves, where light saturation effects reduce utilization for leaves with PAR absorption >225 μmol m-2 s-1. Throughout the manuscript text, figures, and tables, light saturation refers to leaves that absorb more than 225 μmol m-2 s-1 and are therefore unable to utilize all absorbed light for photosynthesis. Light saturation effects are summed across all voxels containing leaves to consider the influence of illumination geometry, direct/diffuse fraction, and incident PAR on IAPAR.

Line 25, page 19050, shadowing effects: where can we see this?

Response: Shadowing effects are illustrated in Movie S1, and quantified in Table S2, based on the magnitude of saturation effects. We have also added a new figure to better illustrate the diurnal and seasonal variability in shadowing (see figure, attached):

New Figure 3. Illumination geometry alters the distribution of light absorption by leaves on a diurnal and seasonal basis. Simulation results for June, September, and Decem-

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ber illustrate the distribution of fractional lAPAR across the model scene under direct illumination conditions, where diffuse light is modeled using observations of aerosol optical depth from Aeronet. Fractional lAPAR exceeds 1 for some voxel columns with high interception of incoming PAR, especially with low sun angles in the morning (09:00 LT) and late afternoon (17:00 LT) that increase the path length through voxels representing emergent and dominant tree crowns.

Fig 2, is not described /explained

Response: The description of Figure 2 has been updated in the Methods section, and the figure caption has been revised to clarify the concepts of light utilization and light saturation effects. The revised caption is:

Figure 2. Probability distribution of average leaf absorbed PAR (lAPAR, red) and absolute light utilization (dashed black) for the September 13:00 DART simulation. Fractional light utilization (blue) for different lAPAR values is plotted on the right y-axis, based on leaf measurements of light saturation from Kitajima et al. [1997]. Absolute light utilization (dashed black) is the product of lAPAR (red) and fractional light utilization (blue). Light saturation reduces the effective leaf absorption for voxels with average lAPAR >225 μmol m-2 s-1.

Fig 5, light saturation effects in this figure are not clear

Response: Figure 5 illustrates light saturation effects in two ways. In panels b and d, light saturation effects generate the difference between cumulative leaf APAR (solid lines) and light utilization (dashed lines). Forest 3D structure changes the estimates of total leaf absorption, the amount of absorbed light available for photosynthesis (utilization), and the vertical distribution of leaf absorption. The vertical distribution of light saturation effects is shown as the red curve in panels a and c for the DART simulations. Under midday illumination (panel a), light saturation effects closely follow the vertical distribution of leaf area (black line). However, at 17:00 LT, light saturation effects are more pronounced for leaves lower in the canopy. The red lines in panels a,c show the

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difference between absorption and utilization curves (black lines in panels b, d).

The caption for this figure (now Figure 6) has been expanded to clarify these points:

Figure 6. Forest 3D structure alters total leaf absorption, light utilization, and the vertical distribution of light saturation effects compared to more simplified representations of the Amazon forest scene. a) Vertical profiles of leaf area density (black) and light saturation effect (red, difference between absorbed and utilized light) for September 13:00 DART simulations. b) DART cumulative lAPAR (black) and light utilization (dashed black); differences between light absorption and light utilization in DART simulations are plotted as the red curve in panel "a" to illustrate the vertical distribution of light saturation effects through the profile of canopy leaf area. DART results were compared to an exponential model of light extinction (blue, following Stark et al., [2012]) and ED2 model simulations (green). Solid and dashed green lines depict cumulative leaf absorption and cumulative light utilization, respectively, for ED2 simulations with 1, 25, and 2500 patches. c, d) Same as 'a' and 'b' for September 17:00 illumination conditions.

Interactive comment on Biogeosciences Discuss., 12, 19043, 2015.

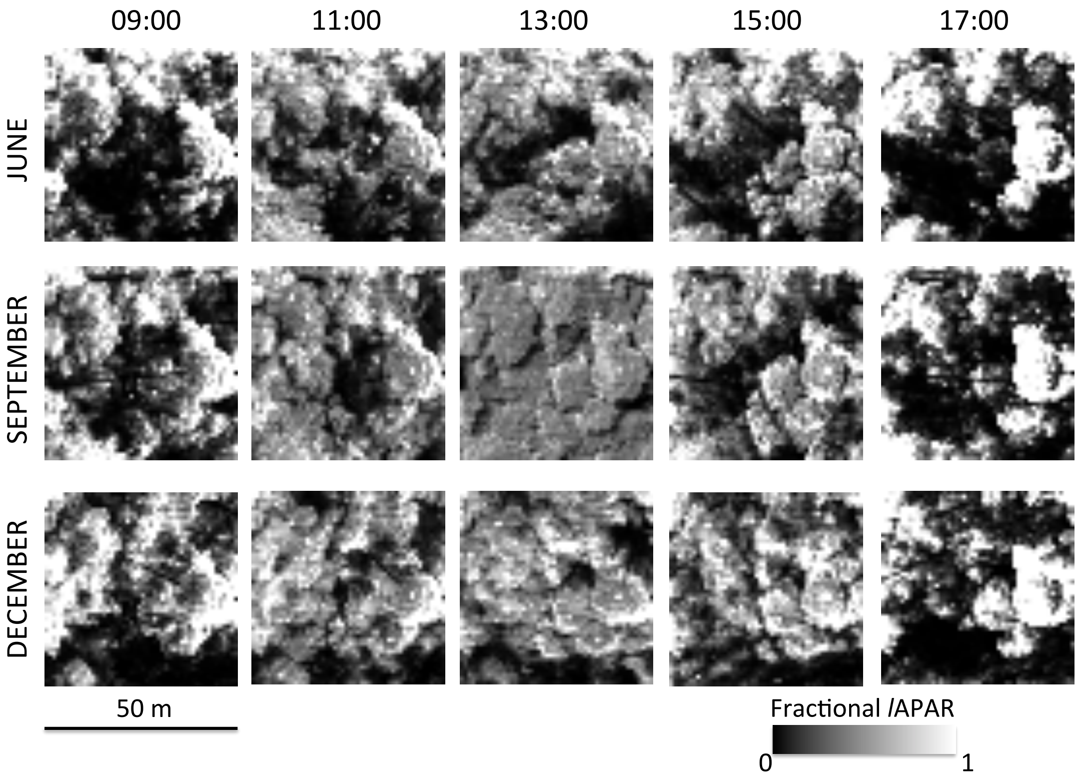

Fig. 1. New Figure (Figure 3) to illustrate canopy shadowing

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