Responses to reviewers **https://doi.org/10.5194/gmd-2019-59**

We thank the two referees for their positive assessments, and suggestions that helped to improve the manuscript. Besides additions and corrections proposed by the referees, we updated two leaf angle analyses due to our discoveries of a significantly larger dataset of measured leaf angles for temperate and boreal species, and of an 'old classic' leaf angle data compilation presented by Ross (1981). To make the leaf angle compilation tables by Ross (1981) available for a wider public, a pdf copy of the tables ('S4_Ross_1981.pdf') is now included as a supplement of this paper.

Anonymous Referee #1

Received and published: 26 May 2019

The paper targets an important issue of possible systematic errors in surface albedo values used in LSM-s that has a direct influence to the estimates of energy fluxes. In general the manuscript is well written and the applied methods are explained.

1.20 "...we found the optical properties of the visible band (VIS; 400-700 nm) to be appropriate." : How do you estimate this? Is it based on the relative error in reflected/absorbed solar energy or some other criteria?

- 1,20: The sentence was modified and now reads: “we found the optical properties of the visible band (VIS; 400-700 nm) to fall within the range of measured values.”

1.20...CLM default and measured estimates were observed," : What is a "measured estimate"?

- The typo was corrected. Should say measured “values”.

1.25 "We also found that while the CLM5 PFT-dependent leaf angle definitions were sufficient..." : Leaf inclination angle is defined as the angle between leaf surface normal and zenith. Do you mean LIA values ?

- Yes, should say leaf inclination angle values. The typo was corrected here in in Table 1 figure caption.

1.25 "... introduce the concept and application of ‘photon recollision probability’ (p)." : The p-theory is already introduced in earlier publications. Here the p-theory is applied and proposed also in discussion to be integrated into LCM-s.

- 1,20 Yes, fair point. The erroneous wording was corrected. It now reads: 1:28-31, “In addition, we propose using separate bark reflectance values for conifer and deciduous PFTs, and demonstrate how shoot-level clumping correction can be incorporated into LSMs to mitigate violations of turbid media assumption and Beer’s law caused by non-randomness of finite-sized foliage elements.”

Introduction 2.5 "... canopy foliage density (e.g. Leaf Area Index (LAI,m 2 /m 2),..." : canopy foliage density (m2/m3) is not leaf area index :: Right bracket is missing.

- Thanks. Typo corrected and bracket added.

2.15 "LSMs (e.g. ... (JULES) (Clark et al., 2011)..." : closing bracket is missing. Check also in other places.

- We added the missing bracket, and checked the text for more missing brackets.

3.10 "While measuring LIA of grasses and crops is relatively straightforward and has been conducted since 1960 using inclined point quadrats (Warren Wilson, 1960)..." : With inclined point quadrats the number of contacts is measured (counted). LIA is estimated from that data.

* The sentence was revised as: ”While measuring LIA of grasses and crops is relatively straightforward and has been conducted since 1960 using inclined point quadrats by measuring the number of vegetation contacts from which the LIA is estimated (Warren Wilson, 1960),..”.

3.20 "...from a leaf or needle in the canopy will interact within..." : "and" seems to be missing.

* This and the following chapter were revised based on reviewer #2 comments.

3.25 "...shoot spectra based on shoot geometry (= p)..." : what is "(= p)"?

* We removed the typo.

M&M 6.5 "For example, dataset by Hovi et al. (2017) contain..." : contains

* Typo corrected.

7.10 "... if spectra were available >2400 nm, it was removed ..." : what was removed?

* Sentence modified. It now reads (8,16): "Note, spectra >2400 nm was removed in effort to harmonize the spectral range of the different data sets."

8.15 "...(and may vary e.g. from 0.12 to 0.28)..." : When STAR is greater than 0.25, then SSA_shoot>SSA_needle according to Eq. (1)!

* We added as sentence to point out and explain this: 10,5-7: "Note, when STAR is greater than 0.25, then SSAshoot > SSAneedle, which may happen if shoot structure is abnormal (e.g. shoot has very short needles which only cover the upper side of the twig (Thérézien et al., 2007).

9.5 "The SSA (shoot) spectra were multiplied with normalized SI spectra for VIS and NIR...": Here and in other places: check that lambda is in the subscript where spectrum is pointed to.

* The lambdas were added to appropriate places.

10.10 "...and the mean measured estimate ..." : What is measured estimate?

* Should say measured 'value', typo was corrected (assumed to refer to 10,30).

13.Table 3. Please present 95% confidence intervals (or at least standard error) for the mean values.

* Standard errors have now been added inside the parentheses.

References 23.10 "Rautiainen, M., Mõttus, M., Yáñez-rausell, L., Homolová, L. and Schaepman, M. E.: Remote Sensing of Environment A note on upscaling coniferous needle spectra to shoot spectral albedo, ," :Yáñez-rausell :: albedo, , :Please check carefully all records in the list of references, there are many formatting errors (journal names, special characters (si× conifers), latin names) and also typos.

* Unfortunately, we had problems with reference management software. All references and citations were corrected.

Anonymous Referee #2

Received and published: 6 July 2019

Many land surface models require vegetation optical properties (leaf and stem reflectance and transmittance, leaf angle distribution), which are used to calculate the absorption and reflection of solar radiation by vegetation. These parameters are an important part of the model and its surface flux calculation, and are also important in determining changes in surface fluxes related to land cover change (e.g., through changes in surface albedo). The Community Land Model (CLM5) is one such model. Optical parameters in CLM5 trace their heritage to Dorman and Sellers (1989) - some 30 years ago, with minimal changes since then. The authors of the present study compare the CLM5 values with published measurements and show that the model parameters do not match observations in several notable discrepancies. This is a very nice study that reminds us that model decisions made many years ago (often for expediency) can be forgotten and perpetuated in subsequent model versions. As this paper shows, there is a need to continually recheck models for their fidelity to observations.

Major comments 1.

An obvious question is whether the updated optical properties improve CLM simulation of surface albedo, or whether there are other factors in CLM that lessen the influence of the optical biases. Simulations with CLM would be quite helpful in this respect, but are not necessary for publication. What is necessary, however, is a discussion of this issue. My intuition is that it is quite likely the model has been tuned over its many versions to reduce the influence of albedo biases. Or if not explicitly tuned, there are likely compensating errors. A particular example is soil color, which is used to obtain soil albedo. No global soil color dataset was available during model development. Instead, soil color originally came from BATS (1986), which as with Dorman and Sellers is undocumented, but soil color was subsequently estimated by tuning the CLM simulated surface albedo to match MODIS (Lawrence and Chase, 2007; JGR, 112, G01023). In dense canopies with high LAI, this many not be too important but in sparse canopies (LAI < 2) soil albedo becomes more important. Also, CLM blends the optical properties of green leaves and wood (stems) to get effective parameters used in the two-stream radiative transfer (RT) model. This is a huge assumption, and is likely a large source of error. Other problems, as the authors have noted, relate to the simplified plane-parallel, homogenous turbid medium assumption used to model RT and the lack of foliage clumping. The authors have a discussion on page 16 about the need to update model parameters. I would like to see this discussion put in the context of other assumptions and simplifications used in the RT model so that readers can assess for themselves how important the new parameters are for improving CLM.

> * We thank the reviewer for the helpful comments and have revised the discussion to reflect these aspects (17-18, 31-14):
>
> "However, whether or not (and if yes, then to what extent) changes in optical properties result in changes to predicted surface albedo requires LSM simulations since LSMs have been tuned to reduce influences of identified biases and possible compensating errors. For example, in the case of CLM, no global soil reflectance dataset was available during model development and soil reflectance data is now based on the tuning of the CLM simulated surface albedo to match MODIS observations (Lawrence and

Chase, 2007). While this may not be too important in dense canopies with high LAI, in sparse canopies (LAI < 2) soil reflectance becomes more important. In addition, we must consider that the major assumptions of 1D RT models themselves are likely to source some error: CLM employs a simplified plane-parallel, two-stream model based on the homogenous turbid medium assumption with isotropic scattering properties. 1D models commonly ignore stems and branches, but the stems are accounted by the CLM RT model: Optical parameters are calculated as a weighted average of leaf and stem areas (i.e. LAI and SAI). This may introduce possible errors (or biases), because i) empirical data and theoretical basis for more accurate definition of SAI is currently lacking (e.g. CLM5 manual, section 29.5.2 (CLM5):" The existing CLM(CN) algorithm sets the minimum SAI at 0.25 to match MODIS observations, but then allows SAI to rise as a function of the LAI lost, meaning than in some places, predicted SAI can reach value of 8 or more. Clearly, greater scientific input on this quantity is badly needed."); and ii) incompatibilities in vegetation structural descriptions in employed RT models (i.e. MODIS LAI is based on 3D RT model whereas CLM employs 1D RT model), which may lead to erroneous assessments of the absorbed, transmitted and reflected fluxes (Pinty et al., 2004; 2006))."

2. The manuscript evaluates the optical properties of grass and crop leaves, but not stems. This omission must be noted and discussed. The implication of the manuscript is that the updated parameter table is better. Modelers may adopt the new parameters, assume they are better, cite this manuscript as the source of the data, but forget that stem optical parameters were not updated for herbaceous plants.

* This is a fair point. We have added a sentence to the Discussion reminding the reader that optical properties for grass and crop stems are not provided due to the scarcity of measurements (18,14-15): "Noteworthy is that we did not provide updated optical property values for the stems of grasses and crops due to the scarcity of measured spectral data for these plant components."

Regarding the implication of this, we have added text to the Discussion that encourages the reader to reflect on whether such parameters are necessary, especially in light of the lack of SAI information and the LAI-SAI weighting employed in the two-stream model (18,15-18): "However, considering that information on SAI is currently lacking, and that grass and crop stems are ignored by today's RT models employed in vegetation remote sensing applications (e.g. MODIS LAI algorithm (Knyazikhin et al., 1999) and PROSAIL (Jacquemoud et al., 2000)), optical properties of grass and crops stems could also be ignored in CLM RT simulations to correspond better with MODIS LAI."

3. The authors mention photon recollision probability (p) in several places throughout the manuscript and make recommendations as to its importance (abstract; introduction; methods; discussion). This is used to upscale from an individual needle to a shoot with many needles – seen in the single scattering albedos (SSA) presented in Table 3 and calculated with eq. (1). The emphasis on p throughout the manuscript, and the recommendation to include it in models, distracts from the manuscript. The simple message of the study is that reflectance, transmittance, and leaf angle used in CLM can, in some cases, differ from measurements and should be improved. This, however, gets conflated with a second message that RT models are using the wrong optical properties and should use shoot values rather than needle values. The author's do not demonstrate that shoot values improve the model compared with needle values. A skeptic is likely to conclude that leaf optical

properties in models are wrongly specified, but why fix them because the model should be using shoot values (though this is not proven). It is fine to maintain the distinction between needle and shoot SSA, but the importance of this has not been demonstrated.

* We agree with reviewer #2 that the reasoning and context for including the photon recollision probability (*p*) was lacking in the first version of the article. Some confusion may have been caused by poor wording choice, which was also pointed out by reviewer #1. The key message we wish to deliver is, indeed, that reflectance, transmittance, and leaf angle values used in CLM can, in some cases, differ from measurements and should be updated. However, we cannot overlook advances taken in the fields of vegetation remote sensing and RT modeling since the SiB-table was formulated - Especially, as some of the advancements (e.g. *p*) are intimately linked with optical properties. Due to lacking literature review and missing citations to published papers, the *p* may have presented itself in our paper as more of a distraction rather than a piece of the puzzle. We remind reviewer #2 that our paper is not just targeting the CLM community, but a broader LSM community, and proper evaluation of optical properties in LSMs requires a more holistic view, which we believe we now provide in the revised version, in a way that does not distract from the suggested improvements to CLM. Specifically, we chose to omit mentioning *p* in Abstract, incorporate an appropriate literature review for the Introduction, and review in the Discussion some of the recent advancements done related to RT schemes in LSMs and explain why land surface modelers should care about *p*.

This is the suggested framing for Introduction (3-4, 20-20):

”In recent years, LSMs have been adapted to incorporate new important processes such as nutrient cycling and land cover dynamics, while the developments in biogeophysical processes like surface radiation schemes have not developed much further (Loew et al., 2014). Criticisms have dealt with incompatibilities in vegetation structural descriptions in the employed RT schemes (e.g. MODIS LAI is based on three-dimensional (3D) RT model whereas CLM employs 1D RT model) (Loew et al., 2014), which may lead to erroneous assessments of the absorbed, transmitted and reflected fluxes (Pinty et al., 2004; 2006)). This incompatibility can be avoided using effective state variables (i.e. effective LAI and effective optical properties), which translate the 3D vegetation information into 1D properties, and correctly represent the effects of vegetation structural heterogeneity within a grid cell (e.g. Pinty et al., 2004; Wang et al., 2018). Effective state variables can be obtained by applying corrections that take into account vegetation non-randomness (e.g. structure) or by measuring the clumped targets (e.g. conifer forest canopy (Majasalmi et al., 2017)). The problem associated with clumping is caused by the turbid media assumption and Beer’s law, which assume foliage elements to be infinitely small and randomly located - neither of which is true for non-gases. While clumping effects may appear at many scales (e.g. shoot, crown, tree, landscape) and may be corrected using various techniques (e.g. Norman and Jarvis, 1975; Chen and Black,1992; Stenberg, 1996; Smolander and Stenberg, 2003; Haverd et al., 2012; He et al., 2012; Wang et al., 2018), there is consensus regarding the existence and significance of clumping on influencing RT of a vegetation media. Noteworthy is that currently clumping effects are not accounted in LSMs.

The MODIS LAI algorithm (Knyazikhin et al., 1999), which is used to parameterize many LSMs, is based on stochastic radiative transfer equation and theory of spectral invariants, which packs 3D information into a 1D equation. This is possible as interactions between photons and canopy elements converge to invariant patterns, which can be quantified using a few wavelength independent parameters, which satisfy the law of energy conservation (Wang et al., 2018). MODIS LAI algorithm for needle forests (section 2.2.6 Biome 6 in Knyazikhin et al., 1999) assumes needles to be clustered into shoots, withshoots being further clustered into crowns. Both clumping corrections are based on spectral invariants theory, which can be interpreted as 'photon recollision probability' (*p*) (Smolander and Stenberg, 2005). Interpretation of p provides physical intuition with the mathematical concept and association with measurable structural vegetation properties (e.g. Lewis and Disney, 2007; Rautiainen and Stenberg, 2005; Smolander and Stenberg, 2005). The *p* is a probability by which a photon scattered (reflected or transmitted) from a leaf or needle in the canopy will interact within the canopy again - In a canopy composed of leaves, a photon scattered from a leaf will not re-interact with the same leaf; however, in a canopy composed of shoots, a photon scattered out from a shoot may have interacted with the needles forming the shoot multiple times. The violations of turbid media assumption and Beer's law by needles clustering into shoots, can be mitigated by changing the basic unit from a needle to a shoot (Nilson and Ross, 1997), by upscaling needle single scattering albedo spectra (SSAneedle(λ)) into shoot single scattering albedo spectra (SSAshoot(λ)) spectra based on shoot geometry (Rautiainen et al., 2012), and by simply replacing SSAneedle with effective SSAshoot in the RT calculation. This correction is applicable to models employing turbid media assumption and Beer's law, and provides simplicity required by LSMs. In addition to MODIS LAI algorithm, the p is currently incorporated into different types of RT modeling schemes such as PARAS models (Stenberg et al., 2016), and Forest Reflectance and Transmittance (FRT) model (Kuusk and Nilson, 2000)."

These are suggested additions for the Discussion (18-19,20-15):

"Generally speaking, the need for improving the RT models employed in LSMs has been acknowledged, and progress has already been made (Yuan et al., 2017; McGrath et al., 2016). For example, a 'domain-averaged structural factor' (i.e. effective LAI accounting for inhomogeneous horizontal distribution such as tree clumping and canopy gaps) and multilayer canopy vertical albedo profile were recently added by McGrath et al., (2016) for ORganising Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE, SVN r2566) model. In their approach, tree crowns were treated as spheroids filled with turbid medium with infinitely small scatterers, and tree trunks were ignored as spectral parameters are extracted from remote sensing data without differentiation between leafy and woody areas. However, as pgap model (Haverd et al., 2012) accounts tree trunks in canopy gap parameterization, the trunks should ideally also be accounted as canopy spectral parameters are determined (Naudts et al., 2015; McGrath et al., 2016). They modeled grasses and crops as homogenous blocks, without internal structure, and defined tunable 'correction factor' to account clumping effects. For CLM, recent advancements were done by Yuan et al., (2017) who compared four representative 1D RT models under the same framework and implemented the appropriate modifications for the CLM4.5 (Oleson et al., 2013). They proposed changes for the employed LAD equation, and two modifications following paper by Pinty et al., (2006) regarding the treatment of incident diffuse radiation and backward scattering coefficient for indecent direct radiation.

As an alternative for empirically based correction factors, which may potentially violate the law of energy conservation, new perspectives for the old challenge are offered by theory of spectral invariants: Based on spectral invariants theory, SSA(λ) is the only parameter that depends on wavelength, while all other parameters are determined by canopy structural factors (Wang et al., 2018). In this paper, we demonstrated how information on shoot-geometry (i.e. *p*) can be used to upscale SSAneedle(λ) into effective SSAshoot(λ) to account for within-shoot scattering, which violates the basic assumptions behind the RT calculation (i.e. non-random ordering of finite-sized needles). The proposed correction, is not currently accounted for in LSMs, and i) can be incorporated by simply replacing SSAneedle with effective SSAshoot in the RT calculation, ii) is applicable to RT models employing turbid media assumption and Beer's law, and iii) provides simplicity required by LSMs. In addition of spectral invariants theory being already incorporated into MODIS LAI algorithm (Knyazikhin et. al., 1999), other desirable features from the point of LSM are that *p*: i) allows generation of consistent products from satellite sensors operating at different spatial resolutions (Ganguly et al., 2008a), and ii) permits compressing 3D information into 1D form across various spatial domains (Ganguly et al., 2008b), and iii) allows measuring, scaling and validation (Stenberg et al., 2016). As remotely sensed products are used as an input in LSMs, advances in RT modeling employed in remote sensing should ideally be reflected by LSM RT parameterizations. In addition, more effort in LSM RT modeling is needed for developing scaling routines to account for seasonal changes of optical properties (and SAI), and for improving parameterizations for snow and ice (Yuan et al., 2017)."

Minor comments

page 1, lines 24-26: The authors refer to needle albedo. Is this single scattering albedo (SSA) or reflectance (R)? Presumably it is reflectance (because the comparison is with CLM) but the authors need to clarify because they distinguish between reflectance and SSA in the manuscript.

* The values are for SSA which is now clarified throughout the manuscript.

page 3, lines 8-10: Leaf angle (LIA) is used more fundamentally to obtain the direct beam extinction coefficient, not just to obtain sunlit/shaded leaf area or for RT model inversion.

* The sentence was modified and now reads (3,7-8): "LIA is needed to obtain the direct beam extinction coefficient, and e.g. to separate foliage area into sunlit and shaded parts.."

page 4, line 6: clarify that leaf and shoot albedo refers to single scattering albedo

* This clarification is now made.

page 4, lines 20-21: This paragraph is a correct history of how the optical parameters used in CLM were obtained. The sentence "Based on CLM grass and crop ..." is correct, but should be rewritten more strongly by deleting "it seems". Change to: "SiBtable class 7, groundcover, was used ..."

* This sentence was corrected following the reviewer's suggestion.

page 5, caption to Table 1: What is meant by "user-friendly version"? Table 1 is the same as in the CLM5 technical description, but collapsed to eliminate equivalent data entries. I believe this is what the authors mean by user-friendly, but that expression is likely to confuse readers.

* Fair point, we have changed the wording from "User-friendly" to "Collapsed".

page 10, line 21: Clarify that 0.07 and 0.05 are from CLM. Compare this sentence with the next sentence, in which the distinction between CLM and observations is clear.

* We modified this sentence so that the distinction between CLM and observations is clear.

page 11, line 1: Only panel c of Fig. 3 is cited. Panels a, b, and d should be cited when discussing the appropriate PFTs.

* Citations for all panels were added to text.

page 11, Figure 2: I did not find this figure to be too helpful. There is too much information (too many symbols, too many different PFTs in a panel, both VIS and NIR, both observations and CLM). Perhaps more panels (one for each PFT or for similar PFTs) would be helpful.

* We agree that the figure was hard to follow. In effort to simplify, we added a new panel for crops and grasses. Each CLM optical type now has its own panel, with symbols modified, and with their own layout improved.

page 13, second line from bottom: Change Fig. 2b to Fig. 4b

* Corrected.

page 15, lines 2-11: Clarify that this text is for leaves only (not for stems)

* Sentences were modified to point out the text is about leaves.

References (new additions)

Chen, J. M., & Black, T. A. Defining leaf area index for non-flat leaves. Plant, Cell Environ. 15(4), 421-429. 1992.

Chianucci, F., Pisek, J., Raabe, K., Marchino, L., Ferrara, C., & Corona, P. A dataset of leaf inclination angles for temperate and boreal broadleaf woody species. Ann.For. Sci. 75(2), 50. 2018.

Ganguly, S., Schull, M. A., Samanta, A., Shabanov, N. V., Milesi, C., Nemani, R. R., ... & Myneni, R. B. (2008). Generating vegetation leaf area index earth system data record from multiple sensors. Part 1: Theory. Remote Sens. Environ 112(12), 4333-4343. 2008a.

Ganguly, S., Samanta, A., Schull, M. A., Shabanov, N. V., Milesi, C., Nemani, R. R., ... & Myneni, R. B. Generating vegetation leaf area index Earth system data record from multiple sensors. Part 2: Implementation, analysis and validation. Remote Sens. Environ 112(12), 4318-4332. 2008b.

Haverd, V., Lovell, J. L., Cuntz, M., Jupp, D. L. B., Newnham, G. J., & Sea, W. The canopy semi-analytic pgap and radiative transfer (canspart) model: Formulation and application. Agric. For. Meteorol. 160, 14-35. 2012.

He, L., Chen, J. M., Pisek, J., Schaaf, C. B., & Strahler, A. H. Global clumping index map derived from the MODIS BRDF product. Remote Sens. Environ. 119, 118-130. 2012.

Jacquemoud, S., Bacour, C., Poilve, H., & Frangi, J. P. Comparison of four radiative transfer models to simulate plant canopies reflectance: Direct and inverse mode. Remote Sens. Environ. 74(3), 471-481. 2000.

Lawrence, P. J., & Chase, T. N. Representing a new MODIS consistent land surface in the Community Land Model (CLM 3.0). J. Geophys. Res. Biogeosciences, 112(G1). 2007.

Lewis, P., & Disney, M. Spectral invariants and scattering across multiple scales from within-leaf to canopy. Remote Sens. Environ. 109(2), 196-206. 2007.

Majasalmi, T., Korhonen, L., Korpela, I., & Vauhkonen, J. Application of 3D triangulations of airborne laser scanning data to estimate boreal forest leaf area index. Int. J. Appl. Earth Obs. 59, 53-62. 2017.

McGrath, M. J., Ryder, J., Pinty, B., Otto, J., Naudts, K., Valade, A., ... & Luyssaert, S. A multi-level canopy radiative transfer scheme for ORCHIDEE (SVN~ r2566), based on a domain-averaged structure factor. Geosci. Model Dev. 2016, 1-22. 2016.

Naudts, K., Ryder, J., McGrath, M. J., Otto, J., Chen, Y., Valade, A., ... & Ghattas, J. A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes. Geosci. Model Dev. 8, 2035-2065. 2015.

Oleson, K. W., Lawrence, D. M.,Bonan, G. B., Drewniak, B., Huang, M., Koven, C. D., Levis, S., Li, F., ... & Thornton, P. E. Technical description of version 4.5 of the Community Land Model (CLM), NCAR Tech. Note NCAR/TN-5031STR, 422 pp., Natl. Cent. for Atmos. Res., Boulder, Colo., doi:10.5065/D6RR1W7M. 2013.

Pinty, B., Gobron, N., Widlowski, J. L., Lavergne, T., & Verstraete, M. M. Synergy between 1-D and 3-D radiation transfer models to retrieve vegetation canopy properties from remote sensing data. J. Geophys. Res. Atmospheres, 109(D21). 2004.

Pinty, B., Lavergne, T., Dickinson, R. E., Widlowski, J. L., Gobron, N., & Verstraete, M. M. Simplifying the interaction of land surfaces with radiation for relating remote sensing products to climate models. J. Geophys. Res. Atmospheres, 111(D2). 2006.

Ross, J. The radiation regime and architecture of plant stands. Junk Publishers, The Hague, pp. 391. 1981.

Wang, W., Nemani, R., Hashimoto, H., Ganguly, S., Huang, D., Knyazikhin, Y., ... & Bala, G. An interplay between photons, canopy structure, and recollision probability: a review of the spectral invariants theory of 3D canopy radiative transfer processes. Remote Sens. 10(11), 1805. 2018.