We deeply appreciate the very careful and constructive suggestions from the Reviewer #1 and Reviewer #2, which help to improve our manuscript. Below we outline our response and the way in which we have addressed each of their comments:

Response to Referee #1's comments RC1

General comments

Liu et al. present a global algorithm to separate under- and over-story Leaf Area Index (LAI) from forest (excluding the tropics). The resulting global LAI datasets are worthwhile and useful for other members in the community (e.g. modeling). Overall, the paper is well written, with clear articulation of the methods, and appropriate and clean visuals. Sometimes the text remains merely descriptive but that may be ok for an algorithm paper. One prerequisite for publication that is not fulfilled is that the authors should make their global datasets available for publication by posting them on a well-accepted data repository (e.g. ORNL DAAC).

Specific comments

Comments 1.1:

- Can you please make the data products available for further use by the scientific community?

Response:

Yes, the global datasets will be posted on http://globalmapping.org/, where also include other products developed by our group, such as our global long-term consistent GLOBMAP LAI dataset (Liu et al., 2012a). The dataset will also be available online on the webpage of our department, Resources and Environmental Science Data Center, Chinese Academy of Sciences.

Comments 1.2:

- It seems that only one field site with understory LAI was available for validation? Are there any other? With regard to all field sites (understory LAI, overstory LAI, NDVI understory), it would help the interpretation if the authors also shortly clarify how these field measurements were taken? For example, how was understory LAI derived in the field? Or how was understory NDVI derived? What was the instrumentation set-up?

Response:

Yes, there is only one field site available for understory LAI validation. There are few LAI measurements available for forest understory, making it challenging to directly validate the satellite retrievals. In fact, our best effects have been made to collect relative field data. Except for the Prince Albert National Park/Canada site used in the manuscript, we also collected understory LAI at several sites from published references, such as Gwangneung Experimental Forest/Korea (Ryu et al., 2014), Tower Hill Botanic Garden, Massachusetts/USA (Herwitz et al., 2004), Florida Georgia/USA (Peduzzi et al., 2010) and Mato Grosso/Brazil (Biudes et al., 2014). However, these measurements cannot be used for validation. The Gwangneung and Tower Hill Botanic Garden sites were measured in 2013 and 1994-1997, respectively, which is out of background reflectance observation period (2000-2010). The location of Florida Georgia site cannot be specified. The Mato Grosso/Brazil site is covered with the evergreen broadleaf forest, which was excluded in our study. Thus, only measurements at Prince Albert National Park/Canada site were used for understory LAI direct validation. Besides field understory LAI measurements, the field understory NDVI measurements at seven sites were also used to further evaluate derived understory LAI (Fig. 13).

The detailed description about the field measurements was added in Table 1 and Table 2 in page 6-8 in the revision, including the measuring method and sampling scheme.

Comments 1.3:

- Related to validation, when using the Kobayashi LAI dataset, was there any ground or field validation of the Kobayashi dataset?

Response:

The Kobayashi larch overstory LAI was compared with ground-based values observed at the Spasskaya Pad experimental larch forest, Yakutsk, Russia in 2000 (Kobayashi et al., 2010). These field measurements were also used in direct validation of our derived overstory LAI in section 3.7 (section 3.6

in the revision).

Comments 1.4:

- In terms of the paper structure: would it make sense to first present the validation results and then go on with the global overview?

Response:

It is more reasonable to present validation before dataset analysis for algorithm paper. This paper focuses on products rather than algorithm. For satellite products, the spatial distribution, seasonal variation and biome distribution could imply the reasonability of the dataset. Besides, the field measurements for validation are limited, although we tried our best efforts. So, we would like to present the global distribution (section 3.2), biome distribution (section 3.3) and seasonal variation (section 3.4) in the front of results, and section 3.5 (seasonal effects of the background reflectivity on the LAI retrieval) will be moved after the comparison and validation.

Comments 1.5:

- English language is generally ok, however in some cases the of the article ‘the’ is redundant. I have indicated some instances in the annotated pdf.

Response:

Thank you for your careful suggestions. The English language will be checked and further smoothed in the revision.

Comments 1.6:

- In the map figures (Figures 4, 5, 6, 9) it would help the presentation if there was a separate legend class for the EBFs that were masked out. Then the reader would immediately know which areas were excluded.

Response:

This suggestion is very good. The EBFs areas were masked out in Figure 4, 5 and 9 in the revision. Figure 6 was deleted according to your suggestions (Comment 7).

Comments 1.7:

- The latitudinal and longtitudinal transects (Figure 6) may not be useful especially since there is no coverage in the tropics. Maybe you could limit the latitudinal transect to the temperate and boreal biomes?

Response:

As you pointed out in the supplement, Figure 6 is not very informative. This figure and related description were deleted in the revision.

Comments 1.8:

- In Figure 7a the frequency peaks at LAI of 6 (for DBF) and at LAI of 8 (for all forest types) seem very artificial. In the tekst you indeed mention that these peaks are there because of set saturation values. Is there a way to get rid of this artifact?

Response:

As it is pointed out, this saturation values are artifacts for unrealistic retrievals. For the very dense canopy, the reflectance value is in the low end, for example, reflectance in the red band is very low due to extremely strong absorption of leaves. Thus, the calculated SR or RSR will be very high, which may result in unrealistic high LAI retrievals. At this minimum value, the LAI is set to the saturation value for the given cover type in the LAI algorithm. These saturation values were excluded in this Figure in the revision (Figure 6a in page 23).

Comments 1.9:

– This may be somewhat challenging but would make the product even more useful; is there a way to estimate pixel-based uncertainty? For example, by assigning uncertainties to all steps in the algorithm (e.g. biome-specific functions, choice of clumping index, uncertainties in MISR background reflectivity, etc.) in an error propagation exercise.

Response:

As the reviewer pointed out, pixel-based uncertainty could improve the usefulness of our product. It is a complex work to evaluate uncertainties in parameters generated from remote sensing observations quantitatively, especially at pixel level (e.g., Miura et al., 2000; Melin et al., 2016). Many factors may introduce uncertainties into the derived LAI datasets, such as LAI algorithm and inputs, mainly including MOD09A1 land surface reflectance, MISR forest background reflectance and clumping index. For biome-specific LAI algorithm, it is hard to evaluate the uncertainties of biome-specific functions. Due to the complexity of radiative transfer process, there are many parameters describing leaf, canopy and soil background in radiative transfer models. Since many of these parameters lack spatial distribution maps at regional and global scale, biome-specific method is widely used in LAI retrieval, and it is hard to evaluate algorithm uncertainties at pixel level. MOD09A1 land surface reflectance product is a key input. But many procedures that convert satellite measured digital counts to reflectance also result in uncertainties, such as reflectance calibration, atmospheric corrections and cloud mask, which is difficult to estimate at pixel-base. For MISR forest background reflectivity, since monthly values were calculated from multi-year valid observations and then used to correct the background effects of MODIS observations, its inter-annual variations may introduce uncertainties into LAI retrieval. Unfortunately, valid MISR observations are too scarce to evaluate these uncertainties (Liu et al., 2012b), and this is the reason that multi-year composition values were used. In this manuscript, we used spatial distribution, seasonal variation, biome distribution and direct validation with field measurements to evaluate the derived dataset. To make the paper more concise, the uncertainty evaluation will not be added. Relative discussion was revised to be more clear in line 14-15 in page 35 in the revision.

Comments 1.10:

- In the Discussion section near the end it could be nice if the authors could highlight some areas of research that could directly benefit from their datasets.

Response:

This suggestion is very helpful. Possible applications of our datasets were added in line 11-14 in page 38 in the revision.

Comments 1.11:

Technical corrections

Some small suggestions are made in the annotated pdf. Please also note the supplement to this comment:

http://www.biogeosciences-discuss.net/bg-2016-448/bg-2016-448-RC1-supplement.pdf

Response:

Thank you for your careful suggestions. The manuscript has been revised according to your comments in the supplement. Table 3 was removed.

Response to Referee #1's comments RC2:

Comments 1.12:

Thank you for the responses to my comments. I would like to elaborate a little bit on the data sharing issue. While I am happy to read that you will be sharing your data on a webpage (http://globalmapping.org/). This webpage seems to be in Chinese and I would hope that the dataset will be put online on a webpage that is easily accessed and understood in English. More than that, perhaps in addition to the personal webpage, or as replacement, I highly recommend the publication of the dataset in a dedicated repository. The journal is dedicated to this avenue of data sharing and it seems natural to follow the guidelines on http://www.biogeosciences.net/about/data_policy.html

Response:

Thank you for this helpful suggestion. We will provide English version of our webpage. The dataset will also be available online on the webpage of our department, Resources and Environmental Science Data Center, Chinese Academy of Sciences.

Response to Referee #2's comments RC3:

General comments

Comments 2.1:

This manuscript examines methods to obtain maps of overstory and understory leaf area index (LAI) for needleleaf and deciduous broadleaf forest at global scales, at 1 km scale, using reflectance data from moderate resolution orbiting NASA remote sensing instruments (MISR and MODIS). It addresses some important issues in ecology and remote sensing of forest canopies and builds on very promising earlier work by Chen, Pisek, and others. The figures are well drawn and most do not need modification;

exceptions include the global maps that ought to be presented larger and with nonmapped areas indicated. There are many tables in the Results section; some repeat a small number of values given in the text and are therefore superfluous.

Response:

According to this suggestion, Figure 4 and 5 (page 18-19) was scaled up to occupy entire pages in landscape mode now. The EBFs were labeled in Figure 4, 5, and 9 (page 34). Table 3 and 4 were deleted since similar results are also presented in Figure 8 and relevant text.

Comments 2.2:

While the goals are worthy and the methods both appropriate and promising, the structure of and writing in this lengthy manuscript make it very frustrating to read. There is too much repetition and the description of methods is sometimes quite unclear, with the use of undefined acronyms and ambiguous passages (highlighted in the Specific Comments section). The authors should try to reduce the volume by at least 25% by avoiding repetition and removing redundant text (and perhaps tables). Above all, the language needs to be far more precise; for example: the origin of one of the main methods (GLOBCARBON) is not even clear to readers in this original submission. There are instances of sloppiness, vagueness, and misleading statements throughout but I think these might become apparent to the authors from a fresh reading. This observation is not about the standard of the English â˘A ˘T that is perfectly adequate â˘A˘ T it is about conveying meaning accurately and unambiguously.

Response:

We really appreciate your careful review and helpful suggestions. The manuscript got revised accordingly, and redundant text was removed to make the language more concise and precise according to the reviewers' suggestions. Figure 6, Table 3 and 4 and relevant text were removed. We really appreciate your efforts in improving the manuscript.

In my opinion it would be a shame not to publish this important work because of an insufficiently high standard of writing, so I recommend a major rewrite. Please see the attached PDF with embedded comments.

Specific Comments

Please see the attached annotated PDF for context. Where the embedded comments differ from those below, the latter shall take precedence.

Comments 2.3:

page 1 . . .but does MISR have sufficient frequency to allow monthly compositing to clear views? If not, some assumptions must have been made about the stability of understory reflectance – what were they?

Response:

MISR does not have sufficient frequency to provide complete monthly retrievals. Here, it is assumed that the forest background changes only from month to month but remain stable in the same month of different years. The global monthly LAI_u maps were produced by averaging the available valid retrievals from 2000 to 2010 for each month. The description of this assumptions was provided in line 10-11 in page 3 (line 14-16 in page 3).

Comments 2.4:

page 1 Isn't this an odd finding? What about lower latitude multi-layer forest? How is "mainly" defined, most biomass, largest extent?

Response:

The largest extent of forest understory is present in boreal forest zones since evergreen broadleaf forests are excluded. The sentence was revised (line 17-19 in page 1).

Comments 2.5:

page 1 This sentence does not seem to make sense: was the first "deciduous needleleaf forests" supposed to read "deciduous broadleaf forests"?

Response:

Yes. This sentence was removed to make the manuscript more concise.

Comments 2.6:

page 1 This is a bit vague: could the authors give it a name and/or indicate a more precise location? There is no need to be vague, even in the abstract.

Response:

The precise location of the dataset was added (line 28 in page 1).

Comments 2.7:

page 1 It is very interesting that understory LAI was retrieved with better accuracy and precision than overstory LAI. If supported by the results, this is a potentially important finding for remote sensing of forest canopies. On the other hand, in view of the inverse result presented in the next sentence, I wonder whether the metrics have been misattributed here, mixing up overstory and understory. Please check this.

Response:

The numbers were corrected and the order of overstory and understory in the last sentence in Abstract was changed to be consistent with the previous one. For comparison with the dataset in eastern Siberia, the absolute and relative error are smaller for overstory LAI than that for understory LAI. Although the R^2 and RMSE are slightly better for understory LAI for direct validation, available field measurements are quite rare, especially for understory LAI. Thus, it is hard to say that the retrieved understory LAI has better accuracy.

Comments 2.8:

page 3 How did Jiao et al. (2014) generate this using MISR data? Even before considering clouds, MISR has a 9-day repeat cycle: a "daily" product is not available. Is this an average for each DOY, accumulated over many years?

Response:

As the reviewer pointed out, Jiao et al. (2014) retrieved the background reflectivity using all available MISR observation for each day, which could not be classified as a daily product. The “daily” was removed.

Comments 2.9:

page 3 I do not think that these "fill values" are in the MISR Land product. This flags many anomalous conditions: failed aerosol/surface retrievals, topographic obscuration of cameras, low albedo thresholds – but does not plug the gaps. It seems more likely that these fill values were generated by Jiao et al. (2014) – please check and correct this statement, if necessary.

Also, MISR does not provide a daily land surface product; its revisit period is 9 days at the equator, so with a 400 km swath it cannot provide daily observations. Do the authors really mean "daily"? This requires further explanation.

The language needs to be precise, or we give readers an incorrect impression.

Response:

As the reviewer pointed out, MISR observations during one day could only cover parts of the globe, so MISR Land product could not be referred as a daily product. Additionally, cloud, cloud shadows, aerosol, sun glitter over water, topographically complex terrain and topographically shadowed regions result in large amount of missing data and invalid retrievals in MISR Land product. For these situation, the procedure was not carried out in retrieval of forest background reflectivity (Jiao et al., 2014). Relevant statement was revised to be precise (line 7-10 in page 3).

Comments 2.10:

page 3 do you mean: all available MISR observations for each DOY were averaged. . ..?

Response:

Yes, it was corrected (line 10-12 in page 3).

Comments 2.11:

page 3 Did Jiao et al. (2014) screen for disturbance, e.g., fires?

Response:

No, disturbance was not screened in Jiao et al. (2014). The disturbance may result in change in understory conditions among years, which may introduce uncertainties in our results. Relevant discussion was added in line 3-4 in page 37 in Discussion section.

Comments 2.12:

page 3 good statement of the assumption (though whether it is a good assumption is debatable).

Response:

The background condition has to be assumed to be stable for each month in different years due to lack of adequate MISR observation. This assumption may introduce uncertainties when the background changes among years, such as fire and other disturbance. Discussion of these issues (in the last paragraph in Page 37) was revised according to your suggestions.

Comments 2.13:

page 3 Actually, more frequently than this if we do not restrict to clear-to-surface observations and consider both Terra and Aqua instruments,

Response:

According to this suggestion, “1-2 days” was changed to “within one day” in line 19 in page 3.

Comments 2.14:

page 3 Good decision: because there is very limited light penetration to the bottom of these canopies, solar wavelength remote sensing provides little information on any understory vegetation in some circumstances.

Response:

Thank you for your agreement.

Comments 2.15:

page 3 MISR-derived. Also: which one? I assume Jiao et al (2014) but it could be Pisek and Chen (2009) – it ought to be explicit. Since the first part is vague, this sentence might well be removed without hurting the manuscript.

Response:

This sentence was removed.

Comments 2.16:

page 4 There are no daily products from MISR – please explain.

Response:

As the reviewer pointed out, we mean the valid MISR observations for each day, which could not be mentioned as a daily product. This sentence was revised (line 17-18 in page 4).

Comments 2.17:

page 4 indeed – but are the authors going to mention or explain the "fill" values mentioned earlier, on page 3?

Response:

The issue of “fill” values has been explained in response to comment 8. This sentence was revised accordingly (line 20 in page 4).

Comments 2.18:

page 4 why would you use this and not bilinear interpolation? These reflectance data are not represented as integers.

Response:

The land cover type product MCD12Q1 could not use the bilinear interpolation. For land surface reflectance product MOD09A1, it is more efficient for the nearest neighbour interpolation than bilinear interpolation for processing of such global multi-year observations.

Comments 2.19:

page 4 This is ambiguous: does this mean that the method was effective, or that the description approximates the operation?

Response:

We mean that the method was effective. The word “effectively” was removed to make it more concise.

Comments 2.20:

page 4 This construction is odd: what are "related references"? Do the authors mean "collated from a variety of third-party surveys"?

Response:

We read many published papers about LAI. Some of them provided field measurements of forest overstory and understory LAI. We collected these measurements to validate our results. “related references” was changed to “relevant published papers”. (please see line 30-31 in page 4).

Comments 2.21:

page 7 Citation required – and maybe an explanation: to which organization or research group does this product belong? Or is this the name given to the method developed in this manuscript? The reader does not know.

Response:

This LAI algorithm is part of the GLOBCARBON project of European Space Agency (ESA). The description was revised to “… based on the LAI algorithm of the GLOBCARBON project of European Space Agency (ESA)”, and citation (Deng et al., 2006) was added (line 4-5 in page 9).

Comments 2.22:

page 7 – but on page 2 we read: "...and GLOBMAP LAI from a combination of Terra/MODIS and NOAA/AVHRR data (Liu et al., 2012a).". Readers do not know whether this GLOBMAP LAI was derived by Liu et al., 2012a, or here. Unfortunately, the manuscript seems to be rife with this kind of sloppiness.

Response:

GLOBMAP is the name of series remote sensing products generated by our group, such as the global long-term LAI dataset (Liu et al., 2012). The forest overstory and understory LAI generated in this manuscript is another GLOBMAP product. And we are also processing other products, including global land cover types, phenology and water surface. “GLOBMAP LAI_o” and “GLOBMAP LAI_u” were changed to “GLOBMAP forest overstory LAI” and “GLOBMAP forest understory LAI”, respectively (line 6-7 in page 9). And “GLOBMAP LAI” in page 2 was changed to “GLOBMAP global long-term LAI” (line 17 in page 2).

Comments 2.23:

page 7 Doesn't VI also have an angular dependence? Or perhaps f_BRDF takes care of that here?

Response:

Yes, function f_{BRDF} quantifies the BRDF effects of VI. Description about f_{BRDF} was revised to "Function f_{BRDF}, which quantifies the BRDF effects of VI_{obs}, …" (line 19-20 in page 9).

Comments 2.24:

page 8 Perhaps it would be good to include citations for each of the inputs here, within each box (where appropriate).

Response:

Citations of the inputs were added in Figure 1 (page 10).

Comments 2.25:

page 8 Is "the" correct, or do the authors mean "a". It is important to use the correct article (definite or indefinite), otherwise readers might be misled. If this is a specific mixture, the reader needs more explanation than provided by the Deng et al. (2006) citation.

Response:

We mean "a". It was corrected (line 4 in page 11).

Comments 2.26:

page 8 So the changing angles were used with a BRDF model to simulate daily reflectivity? This has to be made clear.

Response:

No, these MISR observation angles were used to estimate the forest background reflectivity from all available valid MISR observation for each day (Jiao et al., 2014). The word "daily" is inappropriate, and it was removed (line 14 in page 11).

Comments 2.27

page 9 How was this "combining" done? What was (were) the compositing criterion (criteria)? The average of all values? Otherwise, how to choose the "best" LAIu value? Also, do the authors mean "spatially coherent", or "spatially complete"? It is not clear what "coherent" would mean in this context. Presumably, the reason for using LAIu from multiple years was to obtain as complete a global map as possible. Were all the holes filled? If so, how? If not, how were gaps flagged?

Response:

This comment is very useful. The monthly LAI_u map were produced by averaging valid retrievals for each month during 2000-2010. “Spatially coherent” was changed to “spatially complete”. Almost all the holes filled. The LAI_u were not retrieved over only 0.07% of global needleleaf and deciduous broadleaf forests areas due to missing of MISR background reflectivity during 2000-2010. Besides, some of derived LAI_u exceed the valid range of LAI. These invalid retrievals are mainly occurred in summer, which are probably due to large uncertainties in background reflectivity for dense canopy. These missing values and invalid retrievals were labeled in understory LAI maps. Relevant description was revised (line 23-29 in page 11). Thank you.

Comments 2.28:

page 9 The nature of this noise ought to be clarified so that reader can determine if this is a reasonable thing to do.

Response:

Although 11-year data were used to generate spatially complete monthly MISR forest background reflectivities, there are still missing values. Besides, uncertainties exist in the MISR forest background reflectivity dataset. For example, the reflectivities tend to be unrealistic for dense canopy, which may affect the retrieval of forest overstory LAI (Jiao et al., 2014). So, the monthly forest background SR was scaled to a 10-km resolution to fill the missing values and reduce these uncertainties. Relevant description was revised to be more precise (line 14-17 in page 12).

Comments 2.29:

page 10 Which one? 5, 6, or 7? The "the" implies only one MODIS SWIR band.

Response:

MODIS band 5 was used. “the shortwave infrared band (SWIR)” was revised to “the shortwave infrared band (SWIR, MODIS band 5)” (line 24 in page 12).

Comments 2.30:

page 10 This is vague: name them please (BDF, DNF, ENF?) .

Response:

The forest types, including DBFs, ENFs and DNFs, were specified (line 22-23 in page 12).

Comments 2.31:

page 10 What is the theoretical basis for RSR and the justification for using it for forests, as opposed to SR? Since no citation was provided, this is not clear.

Response:

Since RSR is less sensitive to variable background of forest stands compare to SR (Brown et al., 2000), it is more suitable for LAI retrieval for forests. This sentence was revised and citation was added (line 21 in page 12).

Comments 2.32:

page 10 ok – but you cannot write "the shortwave IR band" in line 2.

Response:

The specific SWIR band used here was added (line 24 in page 12).

Comments 2.33:

page 10 This passage is confusing: it starts by describing the GLOBCARBON LAI algorithm (again?); then describes a method for calculating understory LAI that may relate to GLOBCARBON or to a new method. Please make this clear: try to write so that the meaning is unambiguous.

Response:

This passage was revised to be more clear. The description about GLOBCARBON LAI algorithm was revised and moved to section 2.2. Please see line 9-12 in page 9 and line 22- 27 in page 13.

Comments 2.34:

page 11 This is very confusing: does it refer to the GLOBCARBON LAI, or to the average?

Response:

This refers to the GLOBCARBON LAI algorithm for grass, which is also developed for crop and other non-forest vegetation except shrub (Deng et al., 2006). The descriptions here (line 25-27 in page 13) and in section 2.2 (line 9-12 in page 9) were revised to be more precise.

Comments 2.35:

page 11 This passage requires some sort of introduction, rather than pointing the reader at a figure with unknown relevance. In earlier studies of this kind, it was mentioned that temporal profiles of total and understory reflectivity differ, providing a means of verifying the retrieval of the latter. Is that the intention here, with LAIu?

Response:

The introduction of this passage was added. Figure 3 shows the seasonal cycles of the differences of derived understory LAI based on GLOBCARBON algorithm between shrub and grass. This indicates the seasonal distribution of uncertainties in derived LAI_u. This section was rewritten to be more concise, and relevant statement was added (line 12-29 in page 14 and line 1-5 in page 15).

Comments 2.36:

page 12 How is this relevant to the discussion?

Response:

This section was rewritten, and this sentence was removed (line 12-29 in page 14 and line 1-5 in page 15).

Comments 2.37:

page 12 Perhaps include a sentence explaining the significance of these observations to the goal of obtaining accurate global monthly LAIu?

Response:

The meaning of these observations to derived LAI_u was added in the end of section 3.1. Please see line 3-4 in page 15.

Comments 2.38:

page 12 This is a bit vague, maybe say something about the nature of this procedure, for example, what criteria were used?

Response:

Since a brief introduction of this cloud procedure and description of snow/ice labeling have been presented in the end of section 2.1.1 (line 14-17 in page 4 in our discussion paper), the description about cloud and snow labeling here was removed to make the manuscript more concise.

Comments 2.39:

page 13 which? u or o? or both?

Response:

Understory LAI. It was specified (line 5 in page 16).

Comments 2.40:

page 13 how? is this really worth stating?

Response:

This sentence was removed. Please see line 12-13 in page 16.

Comments 2.41:

page 13 This is a very nice figure but it is far too small: maybe present this figure using an entire page in landscape mode. Also, indicate the unmapped areas on the maps using (e.g.) gray, another unused color, or shading.

Response:

This suggestion is very helpful. Figure 4 was redrawn with EBFs masked, and it was presented using an entire page in the revision (page 18). Thank you.

Comments 2.42:

page 13 Indicate the unmapped areas on the maps using (e.g.) gray, another unused color, or shading.

Response:

EBFs areas in Figure 4 were labeled using another unused color in the revision (page 18). Thank you.

Comments 2.43:

page 13 Previously, 50 - 70 N was described as "boreal".

Response:

These are not the same region. In the previous paragraph, boreal forest zone (50°-70° N) is where forest understory mostly found. Here, we mean the regions where forest overstory show pronounced seasonal variations.

Comments 2.44:

page 15 See the comment on Figure 4; in particular, indicate the unmapped areas on the maps using (e.g.) gray, another unused color, or shading.

Response:

Figure 5 was also redrawn with EBFs labeled with another unused color, and it was presented using an entire page in the revision (page 19).

Comments 2.45:

page 16 See the comment on Figure 4; in particular, indicate the unmapped areas on the maps using (e.g.) gray, another unused color, or shading.

page 16 These do not look right. For example, why do we see large mean overstory LAI values for longitudes corresponding to the Atlantic ocean and Greenland? Please check the calculation of the values used in these profile plots.

Response:

According to the suggestions of Reviewer 1, who pointed out that Figure 6 is not very informative, Figure 6 and relevant text were removed in the revision.

Comments 2.46:

page 16 using which flags? i.e., what was the source of the flags?

Response:

Since the description about cloud and snow labeling have been presented in the end of section 2.1.1 (line 14-17 in page 4 in our discussion paper), this sentence was removed to make the manuscript more concise (line 7 in page 22).

Comments 2.47:

page 17 6 and 8 but not 10, as far as I can see.

Response:

Yes, as you pointed out, small peaks of LAI_o values were presented at 10 for ENFs and DNFs, not DBFs. These saturation values were excluded in the revision, see details in response to comments 2.48.

Comments 2.48:

page 17 So does this mean that this is not real behavior but merely an artefact of the LAI algorithm? The peaks at 6 and 8 do not appear realistic but rather the result of some kind of quantization.

Response:

As it is pointed out, these peaks are artifacts for unrealistic retrievals. For the very dense canopy, the reflectance value is in the low end, for example, reflectance in the red band is very low due to extremely strong absorption of leaves. Thus, the calculated SR or RSR will be very high, which may result in unrealistic high LAI retrievals. At this minimum value, the LAI is set to the saturation value for the given cover type in the LAI algorithm. These saturation values were excluded in the revision, and Figure 7a (Figure 6a in the revision) and relevant text were also revised accordingly (line 9-14 in page 23).

Comments 2.49:

page 17 Isn’t this more a function of tree spacing rather than clumping?

Response:

Yes, tree spacing is also an important factor. This sentence was revised (line 1 in page 24). Thank you.

Comments 2.50:

page 17 This is a description of methods (possibly re-stated).

Response:

Here, the LAI_u and LAI_o were averaged for all pixels for specific forest type for each month in the northern hemisphere. This is a small procedure to generate the seasonal curves, so it is presented in the front of this section. This sentence was revised to be more clear (line 7-10 in page 24).

Comments 2.51:

page 19 Without knowing which one was subtracted, this does not mean anything.

Response:

The description about the difference between the GLOBCARBON LAI and the GLOBMAP LAI_T (GLOBCARBON LAI minus GLOBMAP LAI_T) was revised to be precise. And the difference between the GLOBCARBON LAI and the GLOBMAP LAI_O (GLOBCARBON LAI minus GLOBMAP LAI_O) was also specified. Please see line 14 in page 33.

Comments 2.52:

page 20 Indicate the unmapped areas on the maps using (e.g.) gray, another unused color, or shading.

Response:

EBFs in Figure 9 (Figure 11 in the revision) was also labeled using another unused color in the revision (page 34).

Comments 2.53:

page 22 Was an independent validation of this data set performed? If not, make it clear that this is not intended as a validation data set,

Response:

This dataset generated by Kobayashi et al. (2010) was independent from ours, and it is also validated independently with in situ measurement at Spasskaya Pad experimental larch forest, Yakutsk, Russia (62.26° N, 129.62° E), and compared with MOD15 and CYCLOPES LAI products.

Comments 2.54:

page 22 or just eastern Siberia? see line 3.

Response:

Yes. It was corrected (line 18 in page 28). Besides, captions of Figure 11 (Figure 8 in the revision) and Table 5 (Table 3 in the revision) were also revised to be more precise.

Comments 2.55:

page 22 A new forest understory LAI...

Response:

Corrected. Please see line 19 in page 28.

Comments 2.56:

page 22 Why? Why not include ENF?

Response:

In Kobayashi et al. (2010), the larch pixels were identified with GLC2000 deciduous needleleaf class, and overstory and understory LAI values were only retrieved for these pixels. In our study, MODIS land cover products MCD12Q1 was used to identify forest types. In order to eliminate the effects of different land cover type on the comparison, the region that is given as deciduous needleleaf forests both by GLC2000 and MCD12Q1 were included in the comparison. The relevant description was revised to be more clear (line 16-19 in page 28).

Comments 2.57:

page 24 These are encouraging results – you probably should state N as well.

Response:

This suggestion is good. The numbers of field measurements of overstory and understory LAI were added in relevant descriptions and the caption of Figure 12 (Figure 11 in the revision). Please see line 16 and 20 in page 30 as well as line 5-6 in page 31.

Comments 2.58:

page 26 BRDF, not scattering; I do not think that shadowing can be described as a "scattering effect".

Response:

As you pointed out, this sentence is not clear. We tried to express that shadows from closed canopies make it difficult to observe the signals from understory. This sentence was revised to be more precise (line 11-13 in page 33).

Comments 2.59:

page 26 why? isn't a higher proportion of the understory illuminated in summer?

Response:

In summer, the overstory canopy is generally denser than in spring and autumn, which makes it hard for light to penetrate to the forest floor. It is also difficult for sensors to capture signals of understory through such dense canopies. Thus, the retrievals in the spring and autumn should be more reliable than those in the summer.

Comments 2.60:

page 27 There is a big difference between invalid BRF retrievals (e.g., owing to failed aerosol retrievals) and "missing data" (owing to clouds, topographic obscuration).

Also, please check the use of "daily" in any mention of MISR or MISR-derived products – I do not think it can be correct.

Response:

This sentence was revised to be more precise (line 32-34 in page 36). And the use of "daily" was corrected throughout the paper. Thank you.

Comments 2.61:

page 28 retrievals of what? surface reflectance?

Response:

Understory LAI. It was specified. Please see line 15 in page 37.

Comments 2.62:

page 28 in the northern hemisphere.

Response:

Since it is specified to the boreal forest zones, we do not repeat it to make the paper concise.

Comments 2.63:

page 28 This does not make much sense: we would expect forest understory LAI to reach a maximum in the summer and we would expect greater seasonality at higher latitudes (where needleleef forests dominate). So what is novel here?

Response:

According to this suggestion, this sentence was removed, and Conclusions section was rewritten.

Comments 2.64:

page 28 This just repeats material from the results.

Response:

These sentences were removed, and Conclusions section was rewritten.

Comments 2.65:

page 28 This seems very repetitive: try to state things once, in the most appropriate section.

Response:

These sentences were removed to make it concise. Thank you.

Comments 2.66:

page 29 Absolutely correct. No mention of the potential for field lidar to provide overstory and understory LAI at scales commensurate with the remote sensing data (though 1 km would still be quite tough, even with ~50 m penetration)?

Response:

This suggestion is very helpful. It was added in line 16 in page 38. Thank you.

Technical Corrections

Please see the attached annotated PDF for context.

Comments 2.67:

page 1 (. . .and also remote sensing of forest canopies by inversion of canopy reflectance models).

Response:

Corrected. Please see line 13-14 in page 1.

Comments 2.68:

page 2 A global wall-to-wall. . .. [indefinite article missing]

Response:

Corrected. Please see line 10 in page 2.

Comments 2.69:

page 2 Please give the full product name as well as the code.

Response:

The full product name of MOD15 was added. Please see line 14 in page 2.

Comments 2.70:

page 2 ...using a combination of... [rather than "combining"]?

Response:

Corrected. Please see line 20 in page 2.

Comments 2.71:

page 2 LAI was also estimated... [definite article not required]

Response:

Corrected. Please see line 21 in page 2.

Comments 2.72:

page 2 ; this means. . ..

Response:

Corrected. Please see line 24 in page 2.

Comments 2.73:

page 2 a global...

Response:

Corrected. Please see line 26 in page 2.

Comments 2.74:

page 3 Pisek and Chen, 2009),

Response:

This reference was checked.

Comments 2.75:

page 3 near-infrared [capitalization is not necessary]

Response:

Corrected. Please see line 5 in page 3.

Comments 2.76:

page 3 , making the assumption that understory conditions remain stable over the period.

Response:

Corrected. Please see line 14-15 in page 3.

Comments 2.77:

page 3 "accounted for" more appropriate than "corrected"?

Response:

Corrected. Please see line 24 in page 3.

Comments 2.78:

page 3 Methods

["Data" is usually a subset of "Methods"]

Response:

Corrected. Please see line 1 in page 4.

Comments 2.79:

page 3 Please give the name as well as the code. Also, move this sentence down, to where this product is described.

Response:

The name of MCD12Q1 was added, and this sentence was moved down. Please see line 8-9 in page 4.

Comments 2.80:

page 4 Please define all acronyms on first use.

Response:

All acronyms of IGBP was added. Please see line 11 in page 4.

Comments 2.81:

page 4 on

Response:

Corrected. Please see line 12 in page 4.

Comments 2.82:

page 4 of Jiao et al. (2014).

[must be specific]

Response:

Added. Please see line 13 in page 4.

Comments 2.83:

page 4 This or: This MISR-based...or: The Jiao et al. (2014)...

[otherwise the language impies that this forest background reflectivity data set is a MISR product]

Response:

“The” was changed to “This”. Please see line 13 in page 4.

Comments 2.84:

page 4 What does this mean: on a geographic grid, perhaps?

Response:

Yes, it was corrected. Please see line 15 in page 4.

Comments 2.85:

page 4 resampled (or reprojected) to a geographic grid

– not "pre-processed to the geographic coordinate"

Response:

Corrected to “reprojected”. Please see line 22 in page 4.

Comments 2.86:

page 4 strictly speaking, a geographic grid holds data that are not "projected", so "geographic reference system" might be more appropriate.

Response:

Corrected. Please see line 23-24 in page 4.

Comments 2.87:

page 4 Define acronym on first use:

MODIS Bidirectional Reflectance Distribution Function (BRDF)

Response:

Corrected. Please see line 5 in page 5.

Comments 2.88:

page 7 "Methods" should be the overarching heading for section 2.

This section might be better headed with "Calculation of LAI".

Response:

Since our method estimates the forest overstory and understory LAI rather than calculates them precisely, the heading of this section was revised to "Estimation of LAI" (line 1 in page 9). The heading of section 2 was changed to "Methods".

Comments 2.89:

page 7 Citations required.

Response:

Citations of RSR (Brown et al., 2000) and SR (Jordan, 1969) were added. Please see line 12-13 in page 9.

Comments 2.90:

page 10 repetition typo?

Response:

LAI_T is short for GLOBMAP LAI_T. This sentence was revised to be clearer. Please see line 8 in page 13.

Comments 2.91:

page 11 reference Eq. (4) and (5) here please.

Response:

Added. Please see line 2 in page 14.

Comments 2.92:

page 11 show?

Response:

Corrected. Please see line 12 in page 14.

Comments 2.93:

page 12 Figure

Response:

According to Biogeosciences manuscript preparation guidelines, the abbreviation “Fig.” should be used when it appears in running text (http://www.biogeosciences.net/for_authors/manuscript_preparation.html).

Comments 2.94:

page 12 maps, for each month from January 2010.

Response:

Corrected. Please see line 1 in page 16.

Comments 2.95:

page 12 the

Response:

Corrected. Please see line 4 in page 16.

Comments 2.96:

page 13 for 2010.

Response:

Figure 4 shows the monthly LAI_u maps by averaging valid retrievals from 2000 to 2010 for each month. The caption of this figure in page 18 was revised to be more precise.

Comments 2.97:

page 13 (Figure 5).

Response:

Added. Please see line 15 in page 16.

Comments 2.98:

page 14 Figure 5 needs to go above this text, not below it; Figure 6 is two pages away.

Response:

This paragraph was removed and Figure 5 was moved above in the revision.

Comments 2.99:

page 19 typo. : GLOBCRABON should read GLOBCARBON.

Response:

Corrected. Please see line 19 in page 33.

Comments 2.100:

page 20 typo.

Response:

This sentence was removed to make it more concise.

Comments 2.101:

page 21 based on data from 2008 to 2010.

Response:

Corrected. Please see line 4 in page 35.

Comments 2.102:

page 23 The axes on plot (a) should be rescaled to match the range of values (about 0 - 1).

Response:

The axes were rescaled (page 29).

Comments 2.103:

page 23 or just eastern Siberia?

Response:

Corrected. Please see line 16 in page 29.

Comments 2.104:

page 26 species names in italics please.

Response:

Corrected. Please see line 9 in page 33.

Comments 2.105:

page 26 The quality. . .

Response:

Corrected. Please see line 2 in page 36.

Comments 2.106:

page 27 A combination...

Response

Corrected. Please see line 30 in page 2.36.

Comments 2.107:

page 27 check "daily"

Response:

“daily” was removed. Please see line 3 in page 37.

== end ===

Please also note the supplement to this comment:

http://www.biogeosciences-discuss.net/bg-2016-448/bg-2016-448-RC3-supplement.pdf

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Thank you for your insightful suggestions.

Yang Liu, Ronggao Liu, Jan Pisek, and Jing M. Chen

Separating ~~of~~ Overstory and Understory Leaf Area Indices for Global Needleleaf and Deciduous Broadleaf Forests by Fusion of MODIS and MISR Data

Yang Liu[1], Ronggao Liu[1], Jan Pisek[2], Jing M. Chen[3,4]

[1]State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
[2]Tartu Observatory, Toravere, 61602, Estonia
[3]Nanjing University, Nanjing, 210046, China
[4]Department of Geography and Program in Planning, University of Toronto, Toronto, Ontario, M5S 3G3, Canada

Correspondence to: Ronggao Liu (liurg@igsnrr.ac.cn)

Abstract. Forest overstory and understory layers differ in carbon and water cycle regimes, phenology, as well as ecosystem functions. Separate retrievals of Leaf Area Index (LAI) for these two layers would help to improve modeling forest biogeochemical cycles ~~and~~, evaluating forest ecosystem functions and also remote sensing of forest canopies by inversion of canopy reflectance models. In this paper, overstory and understory LAI values were estimated separately for global needleleaf and deciduous broadleaf forests by fusing MISR and MODIS observations. Monthly forest understory LAI was retrieved from the forest understory reflectivity estimated using MISR data. After correcting for the background contribution using monthly mean forest understory reflectivities, the forest overstory LAI was estimated from MODIS observations. The results demonstrate that the largest extent of forest understory vegetation is ~~mainly distributed~~ present in the boreal forest zones at northern latitudes. Significant seasonal variations ~~are presented~~ occur for understory vegetation in these zones with LAI values up to 2-3 from June to August. The mean proportion of understory LAI to total LAI is greater than 30%. Higher understory LAI values are found in needleleaf forests (with mean value of 1.06 for evergreen needleleaf forests and 1.04 for deciduous needleleaf forests) than in deciduous broadleaf forests (0.96) due to the more clumped foliage and easier penetration of light to the forest floor in needleleaf forests. ~~The magnitude of seasonal variations of overstory LAI is larger for deciduous needleleaf forests than those of evergreen and deciduous needleleaf forests. In contrast, for forest understory, needleleaf forests show larger seasonal variations than broadleaf forests.~~ Spatially and seasonally variable forest understory reflectivity helps to account for the effects of the forest background on LAI retrieval while compared with constant forest background. The retrieved forest overstory and understory LAI values were compared with an existing dataset for larch forests in ~~Northern Eurasia~~eastern Siberia (40°-75° N, 45°-180° E). The retrieved overstory and understory LAI is close to that of the existing dataset, with an absolute error of ~~0.34~~0.02 (0.06), relative error of ~~21.1~~1.3% (14.3%) and RMSE of 0.93 (0.29) for overstory (understory). The comparisons between our results and field measurements in eight forest sites show that the R^2 are 0.52~~62~~ and 0.~~52~~62, and the RMSE are ~~0.62~~1.36 and ~~1.36~~0.62 for overstory and understory ~~and overstory~~ LAI, respectively.

1 Introduction

Forests not only provide habitat~~s~~ and food for animals and fiber~~s~~ and fuel for human beings but also control the global climate and biogeochemical cycles. Most forests, excluding tropical rainforests, have two distinct layers: an overstory layer that mainly consists of arbors, and an understory layer that includes shrubs, grasses and moss. These layers are often treated differently in ecosystem modelling due to their different photosynthetic capacity, carbon residence times, phenology and climatic and environmental responses (Vogel and Gower, 1998; Rentch et al., 2003; Marques et al., 2004; Kim et al., 2016). The understory vegetation plays an essential role in supporting biodiversity, the nutrient cycling and the capability of soil and water conservation in forests (Suchar and Crookston, 2010; Qiao et al., 2014). The Leaf Area Index (LAI) is critical ~~in~~for describing the water, carbon and energy exchange of vegetation with the atmosphere (Braswell et al., 1997; Gitelson and Kaufman, 1998). A ~~G~~global wall-to-wall LAI dataset with separation of forest LAI for overstory and understory layers would help to improve the modelling of forest carbon and water cycles and the evaluation of forest ecosystem functions (Law and Waring, 1994).

Satellite remote sensing provides powerful tools for the estimation of global forest LAI. Several global LAI products have been produced from satellite observations, such as MODIS LAI and Fractional Photosynthetically Active Radiation product MOD15 from Terra-Aqua/MODIS data (Myneni et al., 2002), CYCLOPES (Baret et al., 2007) and GEOV-1 (Baret et al., 2013) from SPOT/VEGETATION data, MERIS LAI from ENVISAT/MERIS data (Bacour et al., 2006) and GLOBMAP global long-term LAI from a combination of Terra/MODIS and NOAA/AVHRR data (Liu et al., 2012a). However, the LAI in these products is the total LAI, i.e., the sum of the forest overstory and understory LAI. Considerable efforts have been made to separate forest overstory and understory LAI at regional scale. For example, the overstory and understory LAI values were estimated by ~~combining~~ using a combination of high spectral and high spatial resolution images using a neural network method and field measurements in Longmenhe forest nature reserve in China (Huang et al., 2011). ~~The~~ LAI was also estimated separately for larch forests in Northern Eurasia using its relationship with the normalized difference water index (NDWI) based on the three-dimensional radiative transfer model (Kobayashi et al., 2010), which assumed that the understory LAI is stable over the entire year; ~~so~~ this means that it is only applicable to deciduous forests with evergreen understory. As forests can vary considerably even within a particular land cover type due to their complex structures and multiplicity of species, a global dataset is highly desirable to describe the heterogeneous spatial distribution of forest overstory and understory.

Multi-angle remote sensing can~~ould~~ capture signals of different forest layers because the observed proportions for different forest layers vary with the viewing angle, making it possible to separate forest overstory and understory LAI on global scale. Forest background reflectivity, which is the reflectance of materials below the forest canopy, including understory vegetation, leaf litter, moss, lichen, rock, soil, snow, etc. was estimated from Multi-angle Imaging SpectroRadiometer (MISR) (Canisius and Chen, 2007; Pisek and Chen, 2009) and ~~Multiangle~~ two-angle observations with Compact Airborne Spectrographic Imager (Pisek et al., 2010a) observations based on the 4-scale model (Chen and Leblanc, 1997). If the forest background reflectivity was~~ere~~ known, LAI could be estimated separately for the forest overstory and understory. The forest background reflectivity over North America has been derived from MISR observations at a spatial resolution of 1° (Pisek and Chen, 2009), and that result has been used to correct the effects of forest background for the determination of the forest overstory LAI over North America (Pisek et al., 2010b).

~~The daily~~ B~~b~~ackground reflectivies~~ty~~ in the red and ~~N~~near-~~I~~infrared (NIR) bands have been retrieved over global forest areas at a resolution of 1.1 km using MISR observations from 2000 to 2010 (Jiao et al., 2014). ~~Severe failed retrievals exist in this product due to the large amount of fill values in the MISR daily land surface products~~Large amount of invalid retrievals exists in these background reflectivity maps for each day because of frequently missing data and invalid retrievals in MISR land surface products, which is due to cloud and aerosol contamination, topographically complex terrain, and other suboptimal illumination conditions. To generate spatially ~~coherent~~ complete 1-km resolution maps, the monthly mean forest background reflectivity was derived by averaging all available valid retrievals for each day~~the valid daily background reflectivity~~ during the 11-year period. This dataset makes it possible to separate the forest overstory and understory LAI globally.

The forest overstory is the main component for carbon fixation and changes seasonally and inter-annually. If the forest background condition is assumed to change only from month to month but remain stable ~~in the same month~~ over the period of different years, the high temporal resolution of overstory LAI can be inferred from satellite measurements with the help of the MISR forest background reflectivity. It takes 9 days for the MISR to acquire global coverage, which makes it challenging to capture the integrated seasonal patterns of global forest overstory. As MODIS provides global radiative measurements ~~in 1-2~~within one day~~s~~, combination of MODIS data and MISR forest background reflectivity could help estimation of forest overstory LAI. In this paper, the forest overstory and understory LAI values were separated for global needleleaf and deciduous broadleaf forest based on the global 1-km MISR forest background reflectivity and ~~the~~ MODIS observations from 2008 to 2010. The monthly mean forest understory LAI was retrieved from the MISR forest background reflectivities in the red and NIR bands. The overstory LAI was determined from the MODIS land surface reflectance with the effects of forest background ~~corrected~~ accounted for by using the MISR forest background reflectivity. Because notable uncertainties may be introduced in the understory LAI retrieval for evergreen broadleaf forests in tropical zones due to the excessive complexity of the forest structure, which makes it difficult to separate it into two layers, the evergreen broadleaf forest type was~~is~~ excluded in this study.

2 ~~Data and~~ Methods

2.1 Data

2.1.1 MODIS and MISR background reflectivity data

~~Several MODIS products and the forest background reflectivity were used in this study.~~ The forest overstory LAI was retrieved from the MODIS land surface reflectance product MOD09A1 from 2008 to 2010.~~ The land cover type was defined by the MODIS product MCD12Q1.~~ ~~The MODIS Surface Reflectance Product~~ MOD09A1 provides global 8-day composite 500-m resolution land surface reflectance in bands 1-7 without the effects of the atmospheric gases and aerosols since February 2000. The land cover type was defined by the MODIS land cover type product MCD12Q1~~The MODIS land cover type product (MCD12Q1)~~, which supplies a yearly land cover classification map with a 500-m resolution of the globe derived through a supervised decision tree classification method with 5 different classification schemes. In this study, the product from the International Geosphere-Biosphere Programme (IGBP) global vegetation classification scheme is selected. The MOD09A1 and MCD12Q1 products are all provided on~~in~~ the Sinusoidal grid.

The forest understory LAI was derived from the MISR forest background reflectivity maps by Jiao et al. (2014). This~~e~~ MISR seasonal forest background reflectivity dataset provides monthly reflectivities in the red and NIR bands over global forest areas at 0.01° (approximately 1 km) resolution ~~with~~ on a~~the~~ geographic grid~~coordinate~~, which represents the reflectance of~~for~~ all materials below the forest canopy, such as understory vegetation, rocks, soils, leaf litter, lichens, mosses, snow, or their mixture. The ~~daily~~ reflectivity was derived from the MISR ~~daily~~ surface bidirectional reflectance factor (BRF) in the nadir and 45.6° forward directions (An and Bf cameras) for each day from 2000 to 2010 based on the 4-scale model. Then, monthly forest background reflectivity was produced by ~~combining~~ averaging 11-year ~~daily~~ valid results for each month to replace a large number of invalid retrievals~~ due to high share of missing data in the MISR Land Surface Products~~ (Jiao et al., 2014).

All MODIS data were ~~pre-processed~~ reprojected to ~~the~~ a geographic~~ coordinate~~ grid, which is the same as the forest background reflectivity. MOD09A1 and MCD12Q1 images from 2008 to 2010 were transformed to geographic reference system~~projections~~ at a 0.005° × 0.005° (approximately 500 m) spatial resolution using ~~the~~ nearest neighbour interpolation and then composed to form global maps. The MOD09A1 land surface reflectance was screened for cloud contamination based on a refined cloud mask for MODIS land surface reflectance products, which ~~effectively~~ identifies ~~the~~ cloudy pixels based on the inflexion point between ~~the~~ clear-sky and cloudy observations of times series of reflectances assemblage for the same location (Liu and Liu, 2013). And the snow/ice pixels were also labelled with MOD09A1 state flags.

2.1.2 Field measurements of forest overstory and understory

Ground LAI measurements of forest overstory and understory were collected from ~~related references~~ relevant published papers for the evaluation of the derived LAI products. These include 28 field LAI measurements of~~for~~ forest overstory at eight sites and 12 measurements of~~for~~ forest understory at Prince Albert National Park, Saskatchewan, Canada. Detailed information about these measurements is presented in Table 1. The overstory LAI measurements provided effective LAI in five conifer-dominated boreal forest sites in Finland, while true LAI was provided for other two deciduous broadleaf forest and one deciduous needleleaf forest sites along a wide latitudinal gradient on the Northern Hemisphere (37.75° N-66.45° N) ~~(Table 1)~~. Here, those effective LAI values were converted to true LAI using the clumping index of the corresponding pixel in the global 500 m-resolution map derived from MODIS Bidirectional Reflectance Distribution Function (BRDF)~~BRDF~~ product (He et al., 2012).

Furthermore, ~~seasonal~~ field measurements of spectral hemispherical-directional reflectance factors of forest understory at seven sites were transferred to understory NDVI, ~~at seven sites were~~ and also used to evaluate the retrieved understory LAI. These sites include different forest types and understory species: a sparse black spruce forest in Alaska (PFRR), a dense black spruce forests in Canada (Sudbury), two southern boreal forest stands in Finland with dominant tree species of Scots pine (Hyytiälä Xeric) and birches (Hyytiälä Herb Rich), hemiboreal needleleaf (pine, Järvselja RAMI Pine) and deciduous (birch, Järvselja RAMI Birch) stands in Estonia, and a temperate mixed forest in Switzerland (Laegern). Table 2 shows the detailed information of these sites. The understory vegetation is mainly composed of herbaceous species at Hyytiälä Herb Rich, Järvselja RAMI Birch and Laegern sites, while it is shrubs, herbs and mosses in other four sites.

Table 1. Summary of field LAI measurements used for validation with the derived forest overstory and understory LAI

Site (Country)	Latitude	Longitude	Biome	Date	Method	CI	Reference
Gwangneung (Korea)	37.75°	127.15°	DBF	2013/4-6	LAI-2200, digital cameras	Y	Ryu et al. (2014)
Prince Albert National Park (Canada)	53.70°	-106.20°	DBF	2000-2003/4-10	Plant Canopy Analyzer	Y	Barr et al. (2004)
Spasskaya Pad experimental larch forest (Russia)	62.26°	129.62°	DNF	2000/6	hemispherical photographs	Y	Suzuki et al. (2001); Kobayashi et al., 2010
Puumala (Finland)	61.53°	28.71°	BF	2000/6	LAI-2000	N	Heiskanen et al. (2011)
Saarinen (Finland)	62.68°	27.49°	BF	2001/7	LAI-2001	N	Heiskanen et al. (2011)
Hirsikangas (Finland)	62.64°	27.01°	BF	2003/8	LAI-2000	N	Heiskanen et al. (2011)
Rovaniemi (Finland)	66.45°	25.36°	BF	2004/5-10	LAI-2001	N	Heiskanen et al. (2011)
Hyytiala (Finland)	61.85°	24.31°	BF	2008/6-7	hemispherical photographs	N	Heiskanen et al. (2011)

CI stands for clumping status. For Biome, DBF, DNF and BF stand for deciduous broadleaf forests, deciduous needleleaf forests and boreal forests, respectively. For CI, the value Y(N) means the clumping effects have (have not) been taken into account in the LAI measurement.

Table 2. Summary of field NDVI measurements used for comparison with the derived forest understory LAI

Site (Country)	Latitude	Longitude	Overstory biome	Dominating understory species	Date	Spectrometer model	Illumination conditions	Sampling	Reference
PFRR (USA)	65.12°	-147.50°	Boreal (ENF) *Picea*	*Vaccinium corymbosum,* moss, and lichen	2010/6	MS-720	clear sky	various floor conditions	Pisek et al., 2016

			mariana						
Sudbury (Canada)	47.16°	-81.76°	Boreal (ENF) *Picea mariana*	*Hylocomium splendens, Ledum groenlandicum,* and *Chamaedaphne calyculata*	2007/6	ASD FieldSpec Pro	clear sky	individual components	Pisek et al., 2010
Hyytiälä Herb Rich (Finland)	61.84°	24.32°	Southern boreal forest (DBF) *Betula pubescens,* and *Betula pendula*	*Vaccinium myrtillus, Vaccinium vitis-idaea, Deschampsia flexuosa,* and *Calamagrostis spp*	2010/5-9	ASD FieldSpec Pro	diffuse	every 0.7 m along 28 m transect	Pisek et al., 2015
Hyytiälä Xeric (Finland)	61.81°	24.33°	Southern boreal forest (ENF) *Pinus sylvestris*	*Vaccinium vitisidaea, Calluna vulgaris,* mosses, and lichens	2010/5-9	ASD FieldSpec Pro	diffuse	every 0.7 m along 28 m transect	Pisek et al., 2015
Järvselja RAMI Birch (Estonia)	58.28°	27.33°	Hemiboreal forest (DBF) *Betula pendula, Alnus glutinosa,* and *Populus tremula*	*Anemone nemorosa, Oxalis acetosella, Agrostis Stolonifera,* and *Sphagnum ssp.*	2014/4-8	ASD FieldSpec Pro	diffuse	every 2 m along 100 m transect	Pisek et al., 2015

Järvselja RAMI Pine (Estonia)	58.31°	27.30°	Hemiboreal forest (ENF) *Pinus sylvestris*	*Ledum palustre, Eriophorum vaginatum,* and continuous *Sphagnum ssp.*	2013/5-9 2014/4-7	ASD FieldSpec Pro	diffuse	every 2 m along 100 m transect	Pisek et al., 2015
Laegern (Switzerland)	47.48°	8.35°	Temperate mixed forest *Fagus sylvatica,* and *Picea abies*	sparse; *Allium ursinum*	2011/9	ASD FieldSpec Pro	clear sky	individual components	Pisek et al., 2016

2.2 ~~Methods~~Estimation of LAI

In this study, the forest overstory refers to the tree canopy, while the forest understory refers to the vegetation below the forest overstory tree canopy, mainly including shrubs, grasses and moss. Forest overstory and understory LAI was estimated using an algorithm for the separation of forest LAI between overstory and understory layers based on the ~~GLOBCARBON~~ LAI algorithm of the GLOBCARBON project of European Space Agency (ESA) (Deng et al., 2006). The derived forest overstory and understory LAI datasets are named GLOBMAP forest overstory LAI~~o~~ (hereafter referred as LAI_o) and GLOBMAP forest understory LAI~~u~~ (LAI_u), respectively. The GLOBCARBON LAI algorithm produces the LAI using the land cover-dependent relationships between the LAI and the Vegetation Index (VI) with consideration of the BRDF effects explicitly based on the 4-Scale model and Chebyshev polynomials (Deng et al., 2006). Forests are combined to four biomes (Coniferous, Tropical, Deciduous and Mixed), and non-forest vegetation is combined into two biomes, i.e., shrub and grass/crop/other vegetated surfaces. Different algorithm coefficients are utilized for each biome type based on separate 4-Scale simulations. The relationship based on Reduced Simple Ratio (RSR) (Brown et al., 2000) is used for forests, while the relationship based on Simple Ratio (SR) (Jordan, 1969) is used for shrub, grasses and other non-forest biomes. First, the effective LAI (L_E) is derived based on the function of VI (SR or RSR):

$$L_E = f_{LE\_VI}\left[f_{biome}(VI_{obs}) \cdot f_{BRDF}(\theta_v, \theta_s, \phi)\right] \quad (1)$$

where f_{LE_VI} is the biome-specific function defining the relationships between L_E and BRDF-modified VI at a specific view and sun angle combination $(\theta_v, \theta_s, \phi)$; here, SR is used for non-forest biomes and RSR for forest biomes. VI_{obs} refers to satellite observed VI (SR or RSR). f_{biome} is the function defining the different algorithms for forest (f_{forest}), shrub (f_{shrub}) and grass (f_{grass}) biomes, which are presented in Sect. 2.2.1 and 2.2.2. Function f_{BRDF}, which quantifies the BRDF effects of VI_{obs}, depends on the angular reflectance behavior of the spectral bands involved.

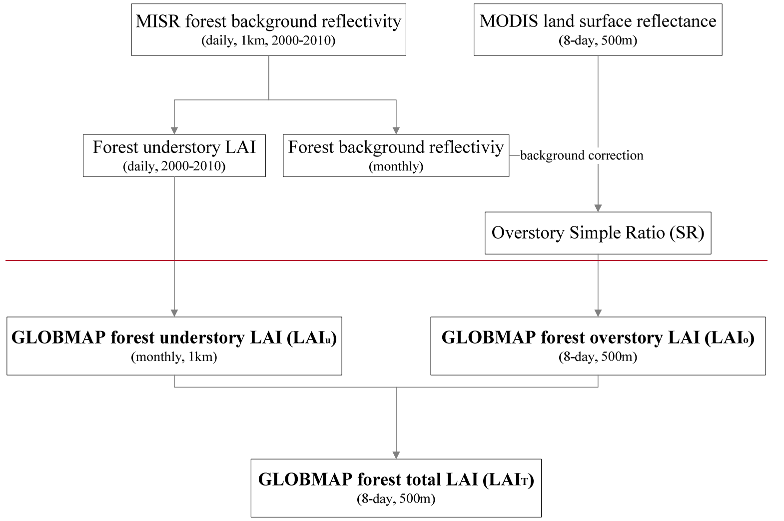
Next, the true LAI is calculated from effective LAI retrievals (L_E) based on clumping index (Ω), which accounts for the vegetation clumping effect on the plant and canopy scales:

$$LAI = L_E / \Omega \quad (2)$$

In this paper, the Ω uses the global clumping index map derived from the MODIS BRDF product (He et al., 2012).

The forest understory LAI was estimated from the MISR forest background reflectivity based on the LAI algorithms for grass and shrub (see Sect. 2.2.1). The forest overstory LAI was derived from the MODIS land surface reflectance data with the effects from the background corrected based on the MISR monthly forest background reflectivity. Then, the forest total

LAI was calculated by summing the forest overstory LAI and understory LAI. Figure 1 shows the general flowchart for the forest overstory and understory LAI separation algorithm.



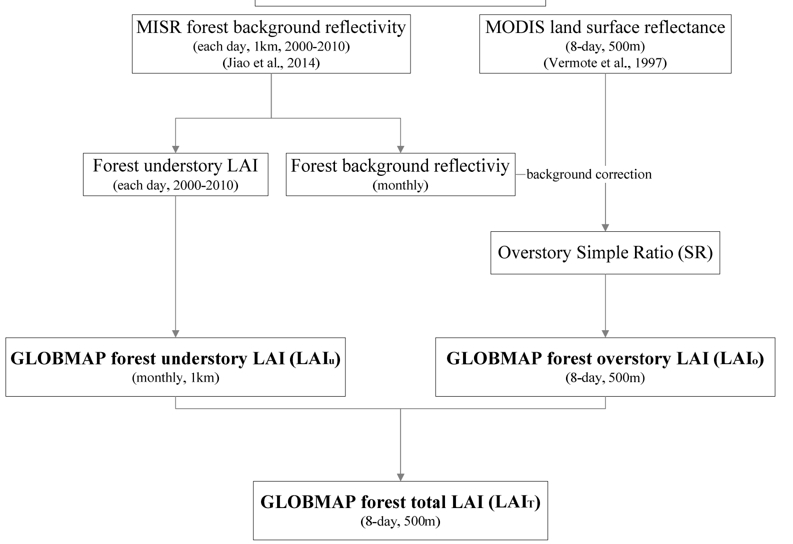


Figure 1. General flowchart for the GLOBMAP forest overstory and understory LAI separation algorithm

2.2.1 Estimation of the forest understory LAI

The LAI derived from the MISR forest background reflectivity (Jiao et al., 2014) should approximate the forest understory LAI. Here, by assuming that the forest understory has a similar composition to ~~the~~ a mixture of shrubland, grassland and moss, its LAI was retrieved from the SR of the forest background based on the LAI algorithms for shrub and grass, which is applicable for ~~shrub,~~ grass and other non-forest biomes except shrub~~(Deng et al., 2006)~~. First, the vegetation index SR for the forest background (SR_B) was calculated using ~~the daily~~ MISR background reflectivity in the red (ρ_{Red_B}) and NIR bands (ρ_{NIR_B}):

$$SR_B = \rho_{\mathrm{NIR}\_B} / \rho_{\mathrm{Red}\_B} \tag{3}$$

Then, the ~~daily~~ forest understory effective LAI was retrieved based on the function of SR_B using the LAI algorithm for shrub and grass, respectively (Eq. (1)). The VI uses SR, and the function f_{LE_VI} in Eq. (1) uses the relationship between L_E and SR for shrub and grass. The effective LAI is directly derived from the SR (here using SR_B) with no corrections except for BRDF (Eq. (4) and (5)). The corresponding solar zenith angle (θ_s), view zenith angle (θ_v) and relative azimuth angle (ϕ) of the MISR cameras, which were used to generate the ~~daily~~ MISR forest background reflectivity, were also used for correcting the BRDF effects in the retrieval of the forest understory LAI (Eq. (1)). Because the observations from two MISR cameras were used in the generation of the MISR forest background reflectivity, including the nadir and 45.6° forward cameras, the forest understory effective LAI was calculated using the geometries in these two cameras separately, and the average value of the two results was used.

$$f_{shrub}(VI_{obs}) = SR_B \tag{4}$$

$$f_{grass}(VI_{obs}) = SR_B \tag{5}$$

After that, the true LAI was calculated from effective LAI retrievals using the global mean value of clumping index for shrubs (0.73) and grasses (0.75) that were derived from MODIS BRDF products (He et al., 2012) (Eq. (2)). Then, these two retrievals for the two biomes were averaged and used as the true LAI for the forest understory (LAI_u). Finally, the global monthly LAI_u maps were produced by ~~combining~~ averaging the valid ~~daily~~ LAI_u from 2000 to 2010 for each month to generate spatially ~~coherent~~ complete maps. The monthly LAI_u are missing only over 0.07% of global needleleaf and deciduous broadleaf forests areas due to missing of MISR background reflectivity during 2000-2010. Besides, some of derived LAI_u exceed the valid range (0-6). These invalid retrievals occurred mainly in summer, which are probably due to the large uncertainties in background reflectivity for dense canopy. These missing values and invalid retrievals were flagged in LAI_u maps.

2.2.2 Estimation of the forest overstory LAI

The effects of the forest background on the MODIS observations were accounted for with the monthly forest background reflectivity maps. Next, the forest overstory LAI was retrieved using modified MODIS observations. In the GLOBCARBON LAI algorithm, the effects of the background are considered by using the background SR value of 2.4 in all of the simulations of the 4-Scale model for all forest types (Deng et al., 2006). To account for the effect of the difference between the standard background SR value (2.4) used in the model simulation and the actual background SR (SR_B), which varies among the sites and seasons, the MODIS observed SR was adjusted by removing the effects of the background (Pisek et al., 2010b):

$$SR_{Overstory\_modified} = (2.4 - SR_B)\cos\theta_v \frac{SR_{MAX} - SR_{obs}}{SR_{MAX} - SR_B} + SR_{obs} \quad (6)$$

where $SR_{Overstory\_modified}$ is the adjusted SR for the forest overstory; SR_{obs} refers to observed SR, which is calculated from the MODIS land surface reflectance (MOD09A1) in the red and NIR bands; and SR_{MAX} is the maximum SR value of the algorithm for a forest type at the view zenith angle (θ_v).

The monthly forest background SR (SR_B) was calculated from the monthly MISR forest background reflectivity in the red and NIR bands. As there are still missing values in monthly SR_B maps, and uncertainties exist in MISR forest background reflectivity dataset, especially for dense canopy (Jiao et al., 2014), the monthly SR_B ~~It~~ was scaled to a 10-km resolution to fill the missing values and reduce these ~~noise~~ uncertainties and then used to adjust the MODIS observed SR (SR_{obs}) based on Eq. (6). Since SR_B represents the signals from all materials below the forest canopy, the effects of the forest background were accounted for. After that, the IGBP land forest classes in the MODIS land cover product (MCD12Q1) were grouped into four forest biomes (conifer, tropical, deciduous and mixed forest). The overstory effective LAI was retrieved from this adjusted MODIS SR ($SR_{Overstory\_modified}$) and corresponding MODIS geometry data using the LAI algorithm for each forest type (Eq. (1)). Since RSR is less sensitive to variable background of forest stands (Brown et al., 2000), ~~T~~the function f_{LE_VI} in Eq. (1) uses the relationship between L_E and RSR (Eq. (7)) for global evergreen needleleaf forests (ENFs), deciduous needleleaf forests (DNFs) and deciduous broadleaf forests (DBFs)~~various forest types~~, and the effective LAI was retrieved from RSR with consideration of the BRDF effects in the shortwave infrared band (SWIR, MODIS band 5) (Eq. (8)).

$$RSR = SR \cdot \left(1 - \frac{\rho_{SWIR} - \rho_{SWIR\min}}{\rho_{SWIR\max} - \rho_{SWIR\min}}\right) \quad (7)$$

$$f_{forest}(VI_{obs}) = SR_{Overstory\_modified} \cdot \left(1 - \frac{\rho_{SWIR} \cdot f_{SWIR\_BRDF}(\theta_v, \theta_s, \phi) - \rho_{SWIR\min}}{\rho_{SWIR\max} - \rho_{SWIR\min}}\right) \tag{8}$$

where ρ_{SWIR} is the SWIR (band 5) reflectance for MODIS; the function f_{SWIR_BRDF}, quantifying the BRDF effects of MODIS band 5, depends on the angular reflectance behaviour of this band; and $\rho_{SWIR\max}$ and $\rho_{SWIR\min}$ are the maximum and minimum values of the SWIR reflectance.

Finally, the true LAI for the forest overstory (LAI_o) was calculated from the effective overstory LAI based on Eq. (2) using the global clumping index map derived from the MODIS BRDF product (He et al., 2012).

2.2.3 Calculation of the forest total LAI

The forest total LAI (GLOBMAP forest total LAI~~$_T$~~, hereafter referred as LAI_T) was calculated by summing the forest overstory LAI and the understory LAI from the same month:

$$LAI_T = LAI_o + LAI_u \tag{9}$$

2.2.4 Estimation of the GLOBCARBON LAI

The LAI was also retrieved from the MODIS land surface reflectance products MOD09A1 for the global forest areas based on the GLOBCARBON LAI algorithm (hereafter referred to as GLOBCARBON LAI) to evaluate the LAI_o, LAI_u and LAI_T. In the GLOBCARBON LAI algorithm, the constant background SR value of 2.4 is used for all forest types without consideration of the spatial and seasonal variations of the forest background (Deng et al., 2006). This constant background SR value is based on field measurements from boreal forests in Canada, which includes effects due to green mosses and the understory (Chen et al., 2002). It does not differentiate forest LAI between overstory and understory. The GLOBCARBON LAI is approximately equal to the forest total LAI with some of the effects due to the forest understory considered (Deng et al., 2006).

3 Results

3.1 Sensitivity analysis of forest understory vegetation composition

~~In the GLOBCARBON LAI algorithm, the non-forest vegetation is combined into two biomes, including shrub and grass/crop/other vegetated surfaces. Different algorithm coefficients are utilized for each biome type based on separate 4-Scale simulations.~~ Since it is challenging to acquire the composition of understory vegetation at global scale, the understory LAI was calculated by averaging the LAI retrievals from MISR background reflectivity based on GLOBCARBON LAI algorithm for non-forest biomes, i.e., shrub and grass/crop/other vegetated surfaces ~~(here referred as grass algorithm)~~ (see details in section 2.2.1). In fact, the structure of understory vegetation is usually complex and spatially disparate rather than half shrubs and half other non-forest vegetation (Peltoniemi et al., 2005). Thus, the smaller the difference of the understory LAI retrieved based on the algorithm between shrub ($LAI_{u,shrub}$) and grass ($LAI_{u,grass}$) is, the less sensitive the LAI_u is to the composition of understory vegetation, which may result in less uncertainties in derived LAI_u. In this section, the difference between $LAI_{u,shrub}$ (Eq. (4)) and $LAI_{u,grass}$ (Eq. (5)) was calculated to evaluate the sensitivity of derived LAI_u to forest understory vegetation composition for global ~~evergreen needleleaf forests (~~ ENFs~~)~~, ~~deciduous needleleaf forests (~~DNFs~~)~~ and ~~deciduous broadleaf forests (~~DBFs~~)~~.

Figure 2 shows the distribution of differences between $LAI_{u,grass}$ and $LAI_{u,shrub}$ for global ENFs, DNFs, DBFs and all these three types of forests combined. The two LAI results are close to each other with the difference concentrated around zero and 82% (94%) of values lies within ±0.2 (±0.3). $LAI_{u,grass}$ is slightly greater than $LAI_{u,shrub}$ for most forest pixels. The annual mean difference is of 0.11 for global forests except EBFs, and DBFs show slightly larger difference (0.12) than ENFs (0.09) and DNFs (0.11).

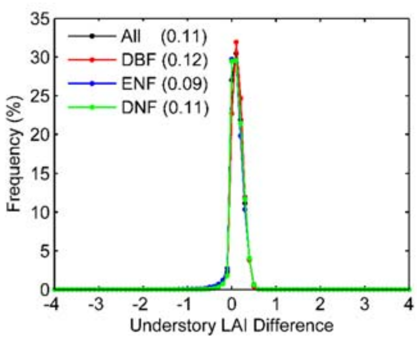


Figure 2. Frequency of differences of derived understory LAI based on GLOBCARBON algorithm between shrub and grass

Seasonal cycles were present in the difference between $LAI_{u,grass}$ and $LAI_{u,shrub}$~~.~~ Figure 3a and 3b ~~refer to~~show ~~the~~ temporal profiles of monthly mean difference between these two algorithms ~~between $LAI_{u,grass}$ and $LAI_{u,shrub}$~~ for various forest types in the northern and southern hemispheres, respectively. ~~Disparity in seasonal curves of the mean difference is presented for various forest types and the two hemispheres.~~ Generally, the difference is ~~relatively~~ larger in summer. In the northern hemisphere, the difference is less than 0.10 due to the sparse understory vegetation from October~~January~~ to March, while it~~.~~ ~~It starts to increase sharply due to the growth of the understory vegetation from April, and~~ reaches the maximum values during May and June with mean difference ranging from 0.20 to 0.28. ~~Then, the difference decreases with the flourishing of overstory canopy, and the value is reduced to less than 0.10 from October to December.~~ The three forest types show noticeable discrepancy in seasonal curve of mean differences. ~~In June and July, the mean difference for DNFs (around 0.25) is larger than that of ENFs (around 0.22), while DBFs show smallest differences with values around 0.19. In contrast, it is generally larger for DBFs that that for needleleaf forests.~~ Large difference is concentrated in June in DNFs, with the largest monthly mean difference up to 0.28. In the southern hemisphere, the mean difference is generally smaller than in the northern hemisphere. For ENFs and DNFs, the monthly mean difference is generally below 0.10. For DBFs, the mean difference shows significant seasonal variations with the opposite seasonal curve compared to the northern hemisphere. Large mean difference is present from August to March, with most monthly mean difference ranging from 0.12 to 0.19. The maximum monthly mean difference appears in December (0.19). This suggests that the uncertainties in derived LAI_u are generally slightly larger in summer and in the northern hemisphere, especially for DNF in the northern hemisphere in June. ~~Large difference is concentrated in June in DNFs, with the largest monthly mean difference up to 0.28.~~

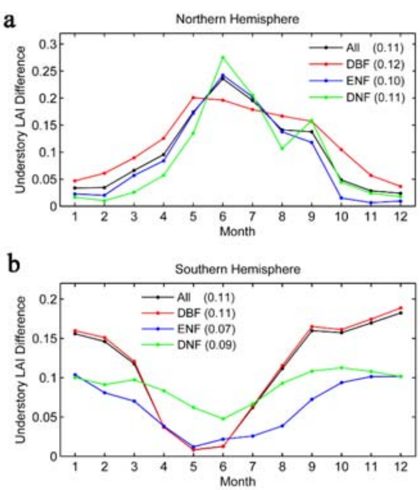


Figure 3. Differences of derived understory LAI based on GLOBCARBON algorithm between shrub and grass: (a) the northern hemispheres; (b) the southern hemispheres.

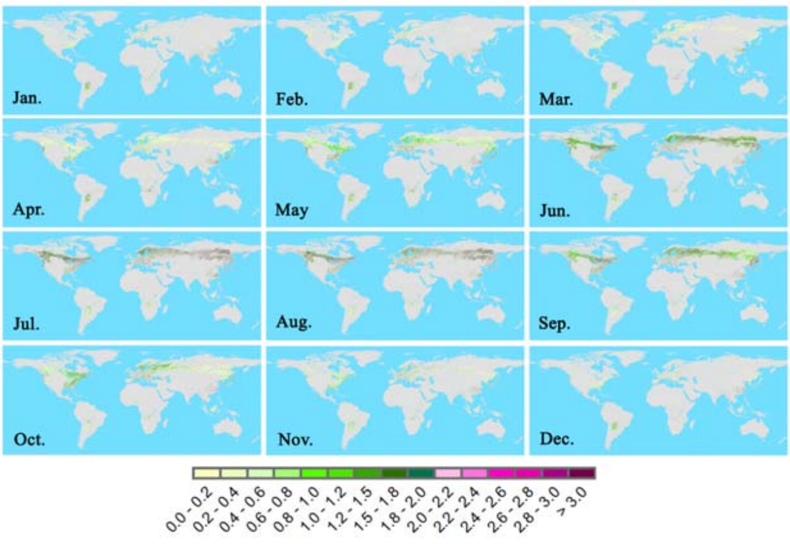
~~In the southern hemisphere, the mean difference is generally smaller than in the northern hemisphere. The area of forests is much smaller, especially for needleleaf forests. For ENFs and DNFs, the monthly mean difference is generally below 0.10. For DBFs, the mean difference between $LAI_{u,shrub}$ and $LAI_{u,grass}$ shows significant seasonal variations with the opposite seasonal curve compared to the northern hemisphere. Large mean difference is present from August to March, with most monthly mean difference ranging from 0.12 to 0.19. The maximum monthly mean difference appears in December (0.19). The monthly mean difference decreases below 0.06 from April to July, and reaches the minimum (0.01) in May.~~

3.2 Global distribution of forest overstory and understory LAI

The monthly LAI_u was estimated from the MISR monthly background reflectivity over the global needleleaf and DBFs area at a spatial resolution of 1 km, and the 8-day LAI_o was retrieved from the MODIS land surface reflectance data MOD09A1 from 2008 to 2010 at a spatial resolution of 500 m. ~~Pixels influenced by snow and ice in LAI_o maps were excluded by using MOD09A1 state flag, and the cloudy pixels were also labeled by a cloud detection procedure (Liu and Liu, 2013).~~

Figure 4 shows the global distribution of LAI_u for each month, and Fig. 5 presents global LAI_o maps for each month from 2010. Significant spatial and seasonal variations ~~are presented~~ exist for forest understory and overstory LAI. Forest understory is mostly found in boreal forest zone~~s~~ in the northern latitudes (50° N to 70° N), especially in summer. In July, 84% of ~~the~~ valid retrievals are concentrated in this zone, and this percentage is still up to 54% in January, when much of the understory vegetation disappears or is covered by snow. The LAI_u~~LAI retrievals~~ is~~are~~ sparse for the southern latitudes (23.5° S to 63.0° S), where the forest area represents only approximately 4% of global forests. Only 2% of the valid LAI_u retrievals are found in this region in July, and this percentage is less than 7% even in January. The LAI_u values mainly range from 0 to 3, with most values occurring in the range 0-1. It could be up to 2-3 in July and August in boreal forests. Notable seasonal variations are found for LAI_u, especially for boreal forests at high latitudes in the northern hemisphere. In this region, the LAI_u is mainly less than 0.5 from November to April. Its value increases starting in May and reaches approximately 1.0 in May with a maximum value of up to 2-3 from June to August. Then, the values decrease in September and are below 1.0 in October. ~~These seasonal variations also demonstrate the importance of seasonal forest background reflectivity in LAI retrieval.~~

The spatial and seasonal patterns of the LAI_o are close to that of the forest total LAI, suggesting that overstory is the dominant component of forest LAI (Fig. 5). Compared with the southern latitudes, the seasonal variations in LAI_o are much more pronounced in the region of 30° to 70° N, where deciduous forests are widely distributed. The LAI_o is approximately 0 from November to March due to snow covers, and its maximum value is greater than 4.0 from June to August. In the southern latitudes (23.5° to 63.0° S), the valid retrievals of the LAI_o are sparse with inconspicuous seasonal variations due to the small forest area.


Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
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2.8 - 3.0
> 3.0

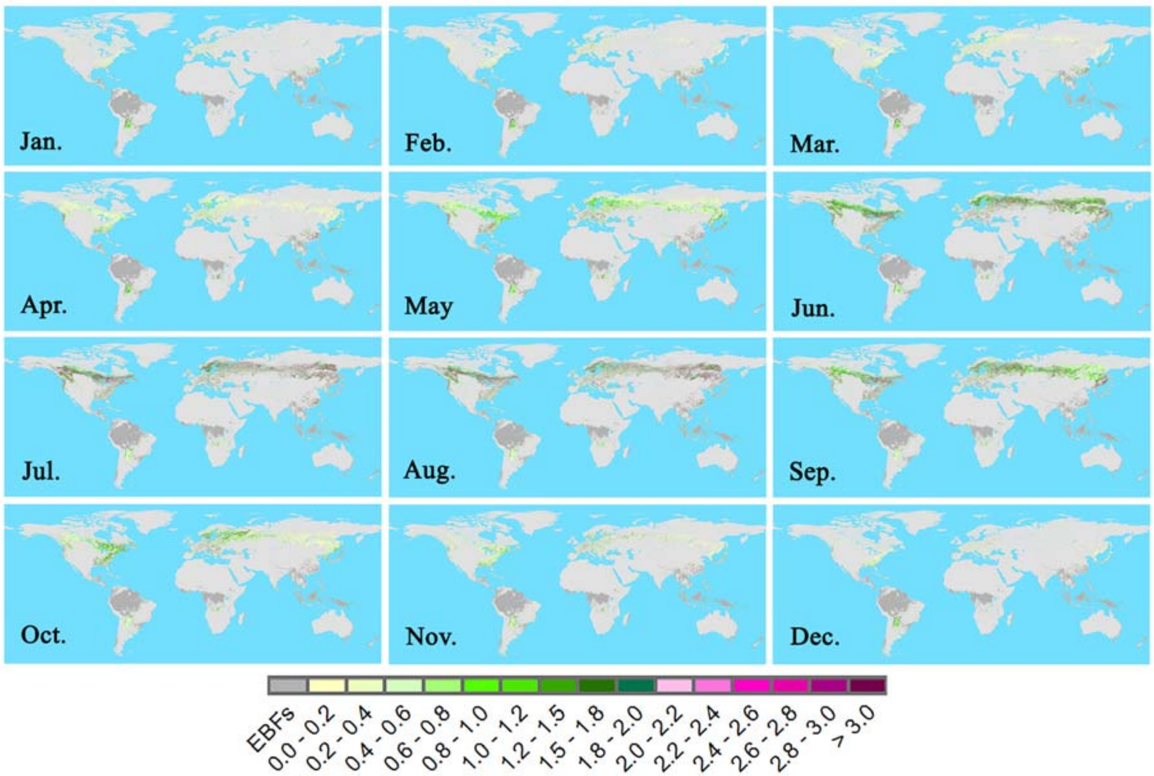


Figure 4. Global monthly GLOBMAP forest understory LAI maps by averaging valid retrievals during 2000-2010 for each month. Because notable uncertainties in the retrieved understory LAI are introduced for EBFs in the tropical zones due to the unreliability of the forest background reflectivities in this biome, the results from EBFs are excluded.

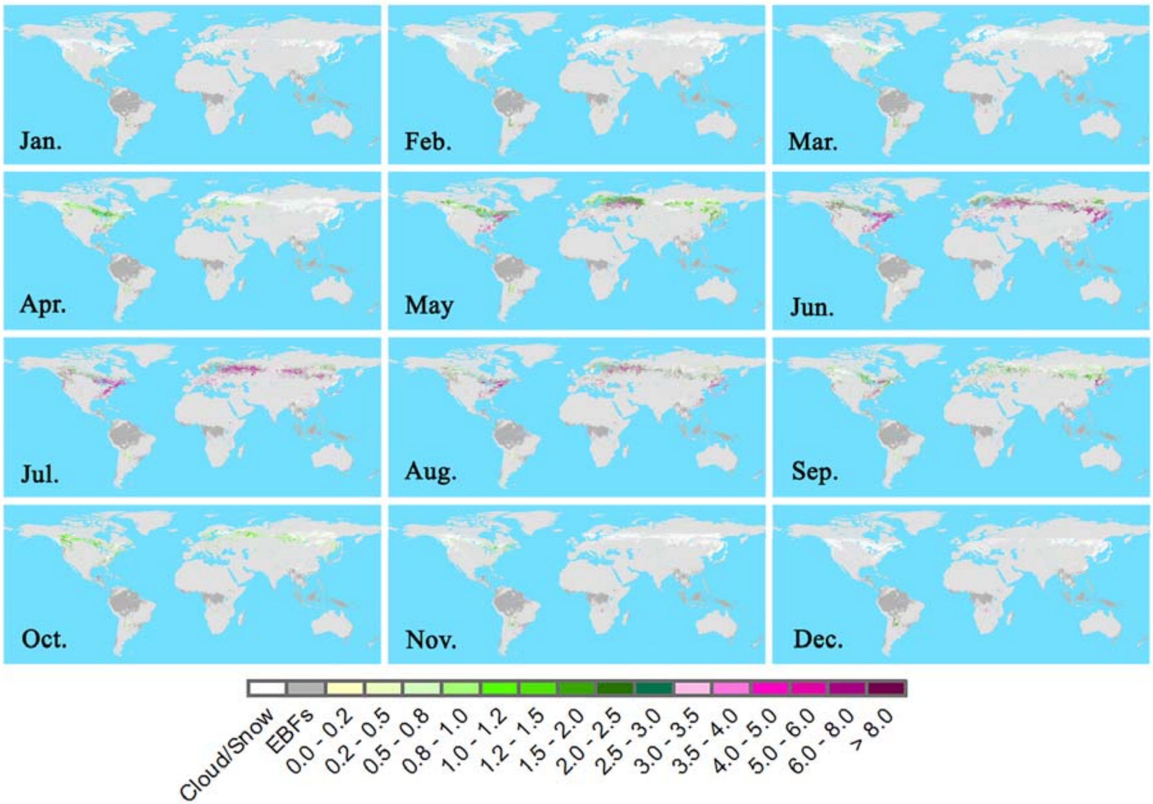
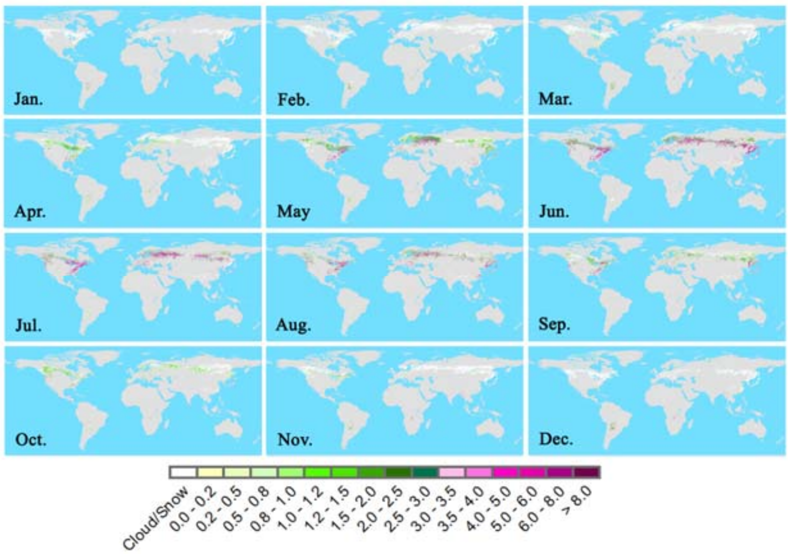


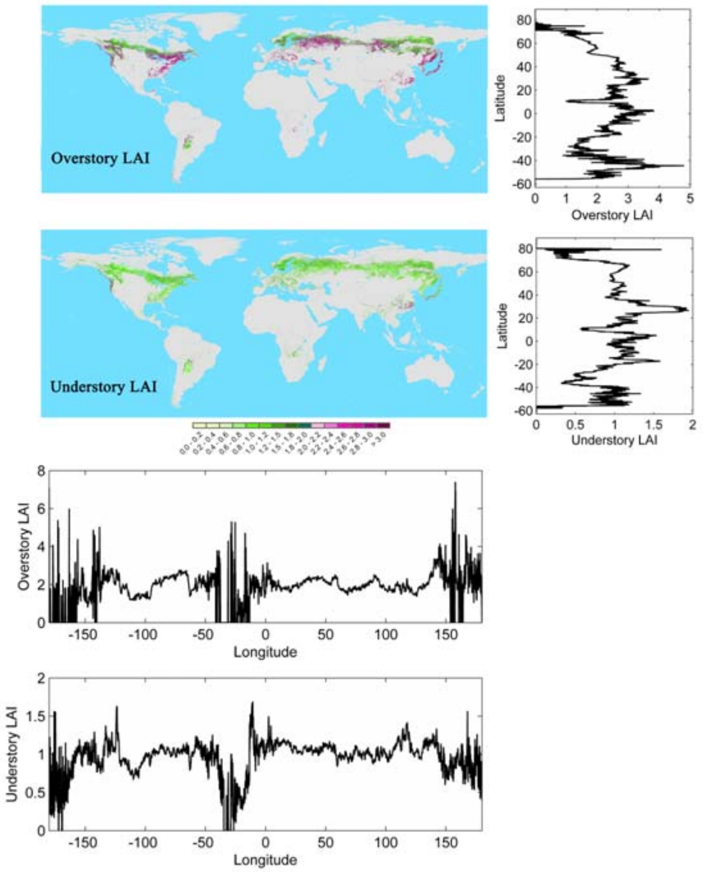
Figure 5. Global monthly GLOBMAP forest overstory LAI maps in 2010, with DOY001 for Jan., DOY041 for Feb., DOY073 for Mar., DOY105 for Apr., DOY137 for May, DOY169 for Jun., DOY185 for Jul., DOY225 for Aug., DOY249 for Sep., DOY281 for Oct., DOY313 for Nov., and DOY345 for Dec. The results from EBFs are excluded.

~~The spatial and seasonal patterns of the LAI$_o$ are close to that of the forest total LAI, suggesting that overstory is the dominant component of forest LAI. Compared with the southern latitudes, the seasonal variations in LAI$_o$ are much more pronounced in the region of 30° to 70° N, where deciduous forests are widely distributed. The LAI$_o$ is approximately 0 from November to March due to snow covers, and its maximum value is greater than 4.0 from June to August. In the southern latitudes (23.5° to 63.0° S), the valid retrievals of the LAI$_o$ are sparse with inconspicuous seasonal variations due to the small forest area.~~

~~The average values of the monthly LAI$_u$ and 8-day LAI$_o$ (2008-2010) were mapped for global needleleaf and DBFs pixels, and the LAI$_u$ and LAI$_o$ patterns were examined along the latitude and longitude ranges. Figure 6 shows the mean LAI maps for the forest overstory and understory, as well as the latitudinal and longitudinal distributions of the mean LAI values for these two layers. The mean LAI$_u$ is around 1.0 for most forests area studied, while LAI$_o$ shows significant spatial variations with mean value ranging from 1.5 to 4.0. Both LAI$_u$ and LAI$_o$ show notable variations with latitude but having different patterns. For the overstory, the LAI$_o$ decreased overall with increasing of latitudes in the northern hemisphere from 30° N to 80° N, which may be attributed to the decrease in the solar radiation and differences in the forest types, which are also primarily determined by the local climate. Between 25° N and 35° N, the mean LAI$_o$ reaches above 3.0 due to the dense forests in southern China and southeastern America. For the understory, the mean LAI$_u$ for boreal forests is around 1.0. The large LAI$_u$ values are concentrated in DBFs and mixed forests in southeastern China with LAI$_u$ up to above 1.5 even 2.0, which forms a peak at subtropical latitude between 25° N and 30° N. The other LAI$_u$ peak is presented in the boreal region (55° N to 65° N), where the LAI$_u$ ranges from 1.0 to 1.2. At southern latitudes (23.5° S to 63.0° S), both LAI$_o$ and LAI$_u$ show unstable variations with latitude, which may be associated with the sparse distribution of forests. Between 15° S and 25° S, small peaks are also presented for LAI$_o$ (2.0-2.8) and LAI$_u$ (1.0-1.5) due to relatively dense distribution of forests. In contrast to different patterns of LAI$_o$ and LAI$_u$ along the latitudinal direction, a similar pattern of these two LAI datasets is shown along the longitudinal direction. The mean LAI$_o$ (2.0-2.8) and LAI$_u$ (1.0-1.5) are relatively stable for regions with forests widely distributed, including north and south America between 130° W and 60° W with LAI$_o$ up to 2.5 to 3.0 and LAI$_u$ ranging 0.8 to 1.0, and Eurasia between 10° E to 140° E with LAI$_o$ around 2.0 and LAI$_u$ around 1.0. Unstable variations are also shown in several longitudinal regions that have sparse forest coverages, such as 137° W-180° W, 10° W-40° W and 150° E-180° E. Since EBFs have been excluded, neither LAI$_o$ nor LAI$_u$ shows stable and distinct peaks in the tropical zone.~~



~~**Figure 5. Global monthly GLOBMAP forest overstory LAI maps in 2010, with DOY001 for Jan., DOY041 for Feb., DOY073 for Mar., DOY105 for Apr., DOY137 for May, DOY169 for Jun., DOY185 for Jul., DOY225 for Aug., DOY249 for Sep., DOY281 for Oct., DOY313 for Nov., and DOY345 for Dec. The results from EBFs are excluded.**~~



~~**Figure 6. Global mean GLOBMAP LAI for the forest overstory (2008-2010) and understory, as well as the latitudinal and longitudinal distributions of the mean LAI values for the forest overstory and understory.**~~

3.3 Distribution of overstory and understory LAI for different forest biomes

The LAI_o and LAI_u values were compared for three major forest types, including ENFs, DNFs and DBFs. The histograms and mean values of monthly LAI_u and 8-day LAI_o (2008-2010) were analyzed over the global forest area for each forest type. ~~Pixels influenced by clouds and snow were excluded.~~

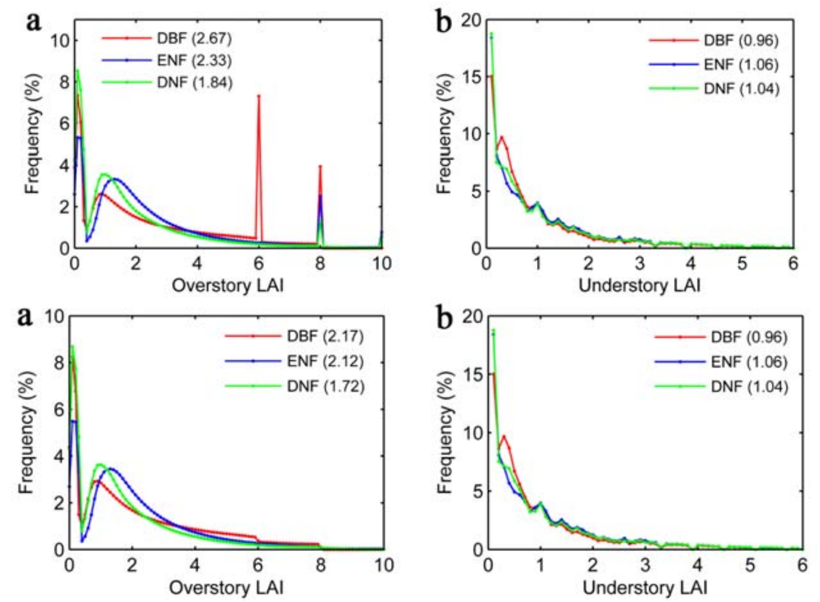


Figure 6~~7~~. Histograms of the GLOBMAP overstory and understory LAI over the global forest area. (a) Forest overstory LAI (2008-2010) and (b) forest understory LAI.

Figures 6~~7~~a and 6~~7~~b show histograms of the LAI_o and LAI_u, respectively. ~~Due to the different geographic distributions, climate and vegetation compositions, the LAI_o and LAI_u show differences for various forest types.~~ For the forest overstory, the LAI values range from 0 to 10, with the majority concentrated in the range of 0-8. Broadleaf forests have more high values for LAI_o than needleleaf forests. The percentage with LAI_o above 3 is up to ~~37~~29.3% for DBFs, while this percentage is 24.1~~7~~% and 18.0~~9~~% for ENFs and DNFs, respectively. The mean value of the LAI_o is also larger for DBFs (~~2.67~~2.17) than for ENFs (~~2.33~~2.12) or DNFs (~~1.84~~1.72). This result is mainly attributed to its short growing season and the low solar radiation at high latitudes, where DNFs are mainly distributed. ~~There are many LAI_o values concentrated at 6, 8 and 10, especially for DBFs, which are the saturation values for dense forests in the summer set in the LAI algorithm (Deng et al., 2006).~~

For the forest understory, the LAI values are smaller than those for the overstory; most LAI_u values are in the range from 0.0 to 3.0. In contrast to LAI_o, the needleleaf forests have more high values for LAI_u than the DBFs; 19% of LAI_u values are above 1.5 for DBFs, while this percentage is 24% for ENFs and 23% for DNFs. The mean value of the global LAI_u is also larger for needleleaf forests (1.06 for ENFs and 1.04 for DNFs) than for DBFs (0.96). This result is probably attributed to the more clumped foliage ~~of the needleleaf forests~~ (Chen et al., 1997) and generally sparse tree spacing of the needleleaf forests, leading to more radiation penetrating through the canopy than for the less clumped broadleaf forests, which is favorable for the growth of understory vegetation (Gower et al., 1999). In addition, the signals from the understory vegetation may be relatively easier to observe by satellite sensors for highly clumped needleleaf forests.

3.4 Seasonal variations of the forest overstory and understory LAI

The temporal profiles for LAI_o and LAI_u for the DBFs, ENFs and DNFs in the northern hemisphere are presented in this section to further evaluate these products. For each forest type, LAI_u values of all pixels covered with specific forest type were ~~was~~ averaged for each month~~, and~~. Similarly, LAI_o was averaged for each 8-day during the period of 2008-2010. These mean LAI values were ~~then used to generate the seasonal curves. The results~~ calculated for the northern hemisphere, and the seasonal curves are presented in this section, where the majority of forests in the world are found.

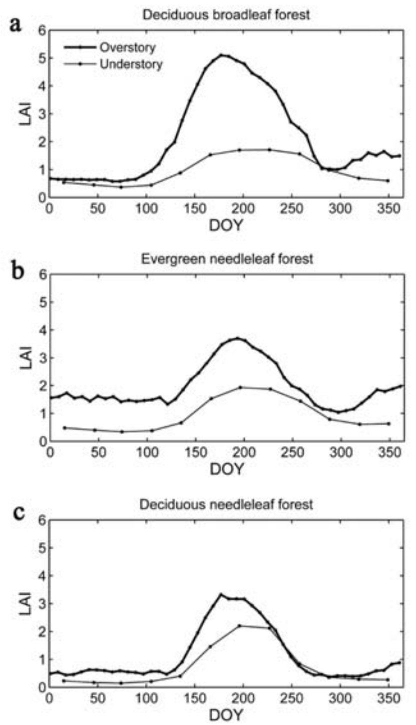


Figure ~~8~~7. Time series of the GLOBMAP overstory (thick lines) and understory (thin lines) LAI for a) DBFs, b) ENFs, and c) DNFs in northern hemisphere.

Figure ~~8~~ 7 shows time series of the overstory (thick lines) and understory (thin lines) LAI~~, and Table 3 presents monthly mean values for the LAI_o and LAI_u for the three forest types~~. Significant seasonal variations of the LAI_o and LAI_u are presented for all three forest types, and the shapes of the curves are similar between the LAI_o and LAI_u for each type. The differences in the magnitude of the seasonal variations and the lengths of the growing seasons are presented for three types. For the LAI_o, DBFs show a larger magnitude of seasonal variation and a longer growing season than needleleaf forests, with LAI_o values approximately 0.6 from November to March and up to more than 4.5 in June and July. For ENFs, the LAI_o values in the summer (approximately 3.0) are smaller than those of broadleaf forests. Although the LAI_o values for ENFs are larger than those of deciduous forests in the winter, the values are still below 2.0, which is probably due to the low sensitivity of satellite measurements in the red and NIR bands to the canopy LAI as a result of the decrease in the foliage chlorophyll in the winter. The magnitude of the seasonal variations is also the smallest for DNFs compared to the other two forest types, where the LAI_o is only approximately 3.0 in July. Because DNFs are usually found at high latitudes or ~~on~~in mountains with low temperatures and precipitations, the lengths of the growing seasons for DNFs are generally shorter than those of DBFs and ENFs.

~~Table 3. Monthly mean GLOBMAP LAI for the overstory and understory of three major forest types in the northern hemisphere, including DBFs, ENFs and DBFs.~~

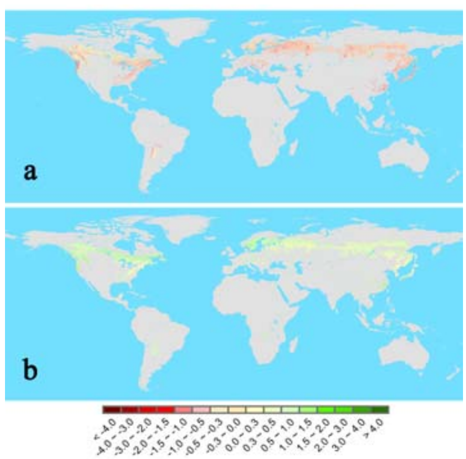
		~~Jan.~~	~~Feb.~~	~~Mar.~~	~~Apr.~~	~~May~~	~~Jun.~~	~~Jul.~~	~~Aug.~~	~~Sep.~~	~~Oct.~~	~~Nor.~~	~~Dec.~~
~~DBFs~~	~~LAI_o~~	~~0.60~~	~~0.65~~	~~0.62~~	~~0.91~~	~~2.41~~	~~4.56~~	~~4.72~~	~~3.91~~	~~2.51~~	~~1.02~~	~~0.78~~	~~1.04~~
	~~LAI_u~~	~~0.54~~	~~0.45~~	~~0.37~~	~~0.44~~	~~0.88~~	~~1.53~~	~~1.70~~	~~1.71~~	~~1.56~~	~~0.98~~	~~0.69~~	~~0.60~~
~~ENFs~~	~~LAI_o~~	~~1.77~~	~~1.42~~	~~1.36~~	~~1.44~~	~~1.76~~	~~2.80~~	~~3.32~~	~~2.81~~	~~1.77~~	~~1.09~~	~~1.03~~	~~1.96~~
	~~LAI_u~~	~~0.48~~	~~0.40~~	~~0.34~~	~~0.38~~	~~0.66~~	~~1.53~~	~~1.93~~	~~1.87~~	~~1.44~~	~~0.79~~	~~0.61~~	~~0.63~~
~~DNFs~~	~~LAI_o~~	~~0.50~~	~~0.64~~	~~0.56~~	~~0.64~~	~~0.98~~	~~2.54~~	~~2.90~~	~~2.22~~	~~1.18~~	~~0.42~~	~~0.48~~	~~0.75~~
	~~LAI_u~~	~~0.23~~	~~0.17~~	~~0.15~~	~~0.21~~	~~0.40~~	~~1.46~~	~~2.20~~	~~2.12~~	~~0.84~~	~~0.36~~	~~0.29~~	~~0.27~~

The seasonal curves for LAI_u are similar to those for LAI_o with smaller magnitudes. In contrast to the forest overstory, the needleleaf forests understory shows higher LAI values (up to 2.2 for DNFs and 1.9 for ENFs in July) than that for broadleaf forests (1.7 for DBFs) in the summer, thus presents larger seasonal variation than that of broadleaf forests, especially for DNFs. The mean proportion of understory LAI to total LAI is generally greater than 30%, indicating that the understory cannot be ignored. This percentage is 36% for DBFs, which is slightly larger than that for DNFs (34%) and ENFs (31%). Differences in the lengths of the growing seasons for LAI_u are also found for various forest types~~ due to their geographic distributions, climates and vegetation compositions~~, which is similar to the forest overstory.

~~3.5 Seasonal effects of the background reflectivity on the LAI retrieval~~

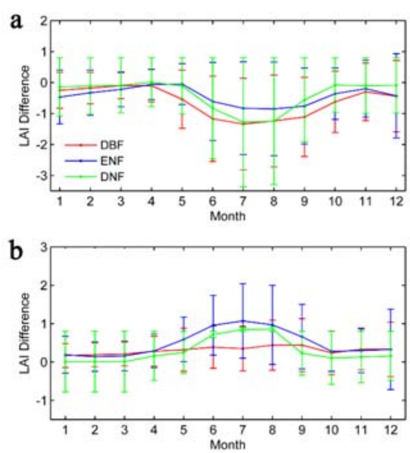
~~The GLOBMAP LAI_T was generated by summing LAI_o and LAI_u in the same month from 2008 to 2010, and the difference between the GLOBCARBON LAI and the GLOBMAP LAI_T was calculated over the global forest area to evaluate the effects of monthly pixel-specific forest background reflectivity on forest LAI retrieval.~~

~~Figure 9a shows a map of the difference between the GLOBCRABON LAI and the GLOBMAP LAI_T over the global forest area. The difference is negative for most forest pixels. This is probably because some forest understory effects have been considered in the GLOBCARBON LAI by using the constant background SR value of 2.4 (Deng et al., 2006), while the GLOBMAP LAI_T includes the LAI for all forest canopy and understory vegetation. Because the standard background SR value (2.4) is based on field measurements in boreal forests in Canada, which includes green mosses and the understory (Chen et al., 2002), the difference is smaller in the boreal forests at high northern latitudes, especially in Canada, with LAI differences within -0.5~0 for most pixels. This difference is larger for broadleaf forests, with LAI differences of up to -1.0, suggesting that the standard background SR in the GLOBCARBON LAI algorithm is more suitable for boreal forests. Yearly mean differences and standard deviations (STDs) for the three forest types over the global forest area are presented in Table 4. The difference between GLOBCARBON LAI and the LAI_T is small for needleleaf forests, with a yearly mean difference of -0.48 for ENFs and -0.59 for DNFs, while this difference is larger for DBFs (-0.68). Figure 10a shows monthly mean differences and STD series in the northern hemisphere. The difference varies for each month for the three forest types. It ranges from 0.0 to -0.5 from November to April, while this difference is larger in the summer, with values of up to -0.8 for ENFs, -1.3 for DNFs and DBFs in July and August.~~



~~**Figure 9. Maps of the differences between (a) the GLOBCARBON LAI and the GLOBMAP forest total LAI (sum of the overstory and understory LAI) and (b) the GLOBCARBON LAI and the GLOBMAP forest overstory LAI. The results for the EBFs are excluded.**~~

~~In addition, the difference between the GLOBCARBON LAI and the GLOBMAP LAI_o was calculated over the global forest area from 2008 to 2010. Figure 9b shows a map of the differences between the GLOBCRABON LAI and the GLOBMAP LAI_o over the globe. Figure 10b shows the monthly mean difference and STD series in the northern hemisphere, and Table 4 shows the yearly mean differences and STD for three forest types over the global forest area. The difference is positive for most forest pixels, which is attributed to the partial signals of understory still included in the GLOBCARBON LAI. Because the difference mainly represents signals from the forest understory, it is also larger for needleleaf forests than broadleaf forests due to their more clumped foliage, especially in the boreal forest zones (Fig. 9b), with yearly mean differences of 0.62 for ENFs, 0.43 for DNFs and 0.35 for DBFs. Notable seasonal variations are also found for the three forest types (Fig. 10b). It is smaller from November to April with a mean difference within 0.4, while it is larger for needleleaf forests during the growing season, with mean differences up to approximately 1.0 for ENFs, 0.8 for DNFs and 0.4 for DBFs from June to August.~~



~~**Figure 10. Monthly mean differences between (a) the GLOBCARBON LAI and the GLOBMAP LAI_T (sum of the overstory and understory LAI) and (b) the GLOBCARBON LAI and the GLOBMAP LAI_o over the global forest area in the northern hemisphere from 2008 to 2010.**~~

~~**Table 4. Yearly means and standard deviations (STDs) of the differences between the GLOBCARBON LAI and the GLOBMAP LAI_T and between the GLOBCARBON LAI and the GLOBMAP LAI_o over the global forest area from 2008 to 2010.**~~

		~~DBFs~~	~~ENFs~~	~~DNFs~~
~~GLOBCARBON LAI-GLOBMAP LAI_T~~	~~Mean~~	~~-0.68~~	~~-0.48~~	~~-0.59~~

	~~STD~~	~~0.59~~	~~0.67~~	~~1.39~~
~~GLOBCARBON LAI-GLOBMAP LAI$_o$~~	~~Mean~~	~~0.35~~	~~0.62~~	~~0.43~~
	~~STD~~	~~0.31~~	~~0.41~~	~~0.37~~

~~The forest understory vegetation and soil background vary with forest type, site and season. Notable uncertainties would be introduced if a constant background were used in the LAI retrieval. The GLOBCARBON LAI products remove partial effects of the forest background, leading to the differences between the GLOBCARBON LAI products and the GLOBMAP LAI$_T$, as well as the LAI$_o$. These differences vary with the forest type, geographic location and season. Due to the different roles of the overstory and understory layers, uncertainties will be introduced into the estimation of the forest water and carbon cycle (Chen et al., 1999). This problem also exists for other LAI products, which do not separate these two layers for forests. Pixel-specific seasonal forest background reflectivity helps to account for the effects of the forest background on the LAI retrieval.~~

3.5~~6~~ Comparison with the overstory and understory LAI of larch forests in Northern Eurasia

~~In this section, t~~The derived LAI$_o$ and LAI$_u$ were compared with an existing overstory and understory LAI dataset, which was estimated for the larch forest with understory vegetation mainly composed with evergreen shrubs such as cowberry and other deciduous species covering eastern Siberia (40°-75° N, 45°-180° E) (Kobayashi et al., 2010). This understory LAI dataset (Kobayashi LAI$_u$) was derived through the relationship with the normalized difference water index (NDWI) on the day of leaf appearance. The overstory LAI dataset (Kobayashi LAI$_o$) was estimated from the relationships between the overstory LAI and the seasonal increases in the NDWI after leaf appearance. The algorithm was applied to SPOT/VGT observations and produced understory and overstory LAI for the larch forests defined in Global Land Cover database for the 2000 (GLC2000) deciduous needleleaf class over ~~Northern Eurasia~~ eastern Siberia with the resolutions of 1/112° in geographic coordinates. ~~The~~ A new forest understory LAI was estimated from the forest background reflectivities on leaf appearance day, which was provided in Kobayashi datasets, from 2005 to 2009 using the algorithm in this paper, and it was compared with the Kobayashi LAI$_u$. The GLOBMAP LAI$_o$ is compared with the Kobayashi LAI$_o$ from 2008 to 2009. The GLOBMAP LAI$_u$ and LAI$_o$ were resampled to the spatial resolution of 1/112° and converted to the same geographic coordinates as the Kobayashi dataset. For each pixel, the GLOBMAP LAI$_o$ and LAI$_u$ was matched with the Kobayashi datasets at the corresponding location and the nearest observational dates to perform a pixel-to-pixel comparison. Those pixels only labeled as DNFs both in MCD12 and GLC2000 were used. Figure ~~11~~8 shows the density scatter plots of the two LAI datasets, and the statistical analysis results are shown in Table ~~5~~3. For understory LAI, both datasets are concentrated in LAI ranges of 0.0-1.0. The comparison shows good agreement with a high density of points dispersed along the 1:1 line and a root mean square error (RMSE) of 0.29. The mean GLOBMAP LAI$_u$ (0.48) is also close to that of Kobayashi LAI$_u$ (0.42), leading to an absolute error of 0.06 and a relative error of 14.3%. For overstory LAI, the majority of the points are distributed in the range from 0.0 to 4.0, which represents the notable seasonal variations of the foliage in this DNFs. The area with the highest density (dark red) is also along the 1:1 line, especially in the LAI range from 0.0 to 3.0, which indicates that the majority of the GLOBMAP LAI_o agrees with the Kobayashi LAI_o. The mean value of the GLOBMAP LAI_o is 1.95, and this value is 1.61 for the Kobayashi LAI_o, resulting in an absolute error of 0.34 and a relative error of 21.1%. Relatively high densities are also found in the Kobayashi LAI_o of 4.0, which can probably be attributed to the relatively concentrated distributions of high LAI values in maximum values in the Kobayashi LAI algorithms. Some points with relatively low densities (blue) stray from the 1:1 line, and the mean value of the GLOBMAP LAI_o is slightly higher than that of the Kobayashi dataset, indicating that the Kobayashi LAI_o is slightly smaller than the GLOBMAP LAI_o. The maximum value of the Kobayashi LAI_o is 4.0 based on the statistics from 2008-2009, while the maximum value of the GLOBMAP LAI_o is 10.0, with the majority in the range from 0.0 to 6.0. To avoid the influence from this difference, a statistical analysis was performed using only the pixels with overstory LAI ranging 0.0 to 4.0 for the two datasets. ~~Table 5 shows the new results.~~ The mean values of the overstory LAI for the GLOBMAP LAI_o (1.53) and the Kobayashi LAI_o (1.51) are very similar, with an absolute error of 0.02 and a relative error of 1.3%~~. In addition~~, and ~~the~~ RMSE decreased from 1.42 to 0.93.

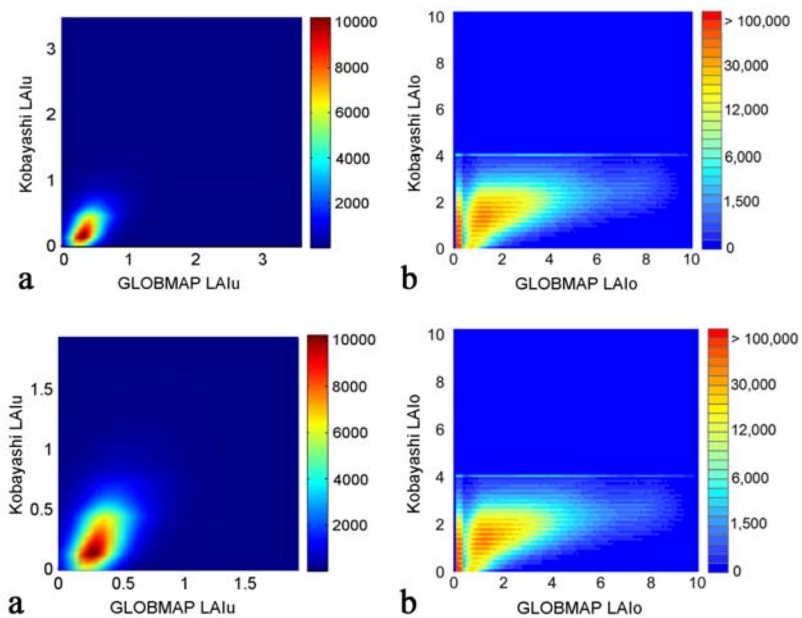


Figure ~~11~~8. Comparison between the GLOBMAP LAI_o and LAI_u with the Kobayashi datasets (Kobayashi et al., 2010) over the larch forest region in ~~North Asia~~eastern Siberia: (a) Understory LAI and (b) Overstory LAI.

Table 3~~5~~. Pixel-by-pixel comparison of the GLOBMAP LAI_o and LAI_u with the Kobayashi datasets (Kobayashi et al., 2010) over the larch forest in ~~Northern Eurasia~~eastern Siberia.

	LAI Range	Linear regression	LAI Mean	
Understory	0-6	y=0.5114x+0.1774	GLOBMAP	0.48
		RMSE=0.29, r=0.51	Kobayashi	0.42
Overstory	0-10	y=0.2549x+1.1113	GLOBMAP	1.95
		RMSE=1.42, r=0.51	Kobayashi	1.61
	0-4	y=0.3412x+0.9833	GLOBMAP	1.53
		RMSE=0.93, r=0.46	Kobayashi	1.51

3.6~~7~~ Validation with field measurements

It is challenging to directly validate the satellite LAI products with spatial resolutions from several hundreds of meters to kilometers against ground measurements due to the uncertainties from scaling, heterogeneity, geolocation and the limited spatial and temporal sampling of ground data (Privette et al., 2000; Weiss et al., 2007). When it comes to the forest overstory and understory LAI, this work is even more challenging due to the lack of separate field measurements for these two layers, especially for understory LAI. In this section, the GLOBMAP LAI_u and LAI_o were compared with field LAI measurements extracted from related references at eight forest sites that cover major forest types except for EBFs. Additionally, the understory LAI (estimated field LAI_u) values were also estimated from the field understory NDVI measurements (field NDVIu) at the seven sites (Table 2), and then compared with the GLOBMAP LAI_u. The algorithms for shrub and for grass/crop/other vegetated surfaces were applied and the mean value of the two retrievals was used as understory LAI. To reduce the uncertainties from heterogeneity and geolocation, the LAI retrievals on 3×3 km pixels around the site were averaged and then compared with the ground data. For those field measurements that provide mean LAI for a month or a period of time, the mean values of LAI retrievals during these periods were calculated for comparison.

For forest understory, the LAI measurements (N=7) at Prince Albert National Park, Canada (53.70° N, 106.20° W) in April to October from 2000 to 2003 were extracted from figures in Barr et al. (2007). The mean values of field understory LAI were calculated for each month from April to October and then compared with the monthly mean GLOBMAP LAI_u at corresponding geolocations. Figure ~~12a~~ 9a shows the results of comparison. The plots are close to the 1:1 line, with a slope of 0.96 and an offset of 0.17. The R^2 is 0.62 and RMSE is 0.62. For forest overstory, the LAI measurements (N=28) at eight sites from 2000 to 2013 were compared with the GLOBMAP LAI_o derived from MOD09A1 land surface reflectance obtained in the nearest time periods. Figure ~~12b~~ 9b shows the comparison results for forest overstory LAI. GLOBMAP LAI_o seems to slightly overestimate the ground data, with a slope of 1.22 and an offset of -0.07. The R^2 is 0.52 and RMSE is 1.36. The LAI_o generally agrees well with the ground data for overstory LAI less than 2.0, with plots close to the 1:1 line. On contrary the differences between the LAI_o and ground data increase when overstory LAI is greater than 2.0. Similarly, the differences between the LAI_u and the field measurement are also smaller for understory LAI less than 1.5 than those approximately 2.0 (Fig. ~~12a~~9a). These results could be probably attributed to the larger uncertainties in reflectivities of the forest background for dense canopies (Jiao et al., 2014), which will affect the understory and overstory LAI retrieved for forest with high LAI values. In addition, the differences in temporal period for field measurements and satellite observation also affect the comparisons, especially for understory LAI which uses the multi-year average values.

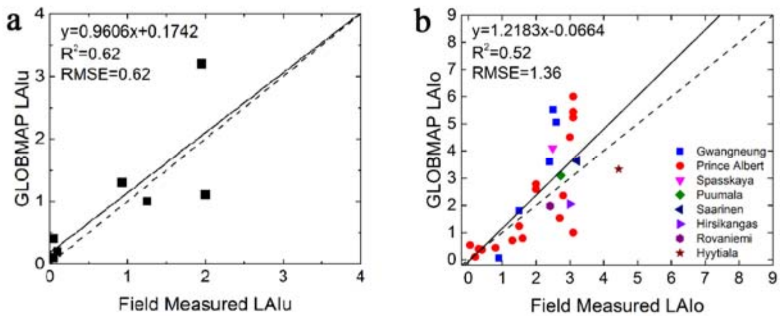


Figure ~~12~~9. Comparison of the GLOBMAP LAI$_u$ (LAI$_o$) and ground LAI data: (a) results for understory LAI at Prince Albert National Park, Canada (N=7); (b) results for overstory LAI (N=28).

Figure ~~13~~ 10 presents the time series of GLOBMAP LAI$_u$, field NDVI$_u$ and estimated field LAI$_u$ at seven forest sites. Generally, GLOBMAP LAI$_u$ shows reasonable seasonal curves, and is consistent well with the shapes of field NDVI$_u$ and estimated field LAI$_u$. Notable seasonal variations are represented with GLOBMAP LAI$_u$, which could characterize the seasonal curves of dominated deciduous understory vegetation at these sites except Laegern. At the northernmost boreal forest site PFRR (65.12° N, 147.5° W), the length of growing season for understory is short, with GLOBMAP LAI$_u$ greater than 1.0 only in June, July and August. The GLOBMAP LAI$_u$ overestimates the estimated field LAI$_u$ at this site. At the most southern site Sudbury (47.16° N, 81.76° W), although the overstory dominated species (black spruce) is the same as the PFRR, the GLOBMAP LAI$_u$ is greater than 1.0 until October. Our result in July is very close to the estimated field LAI$_u$ in day of year (DOY) 177.

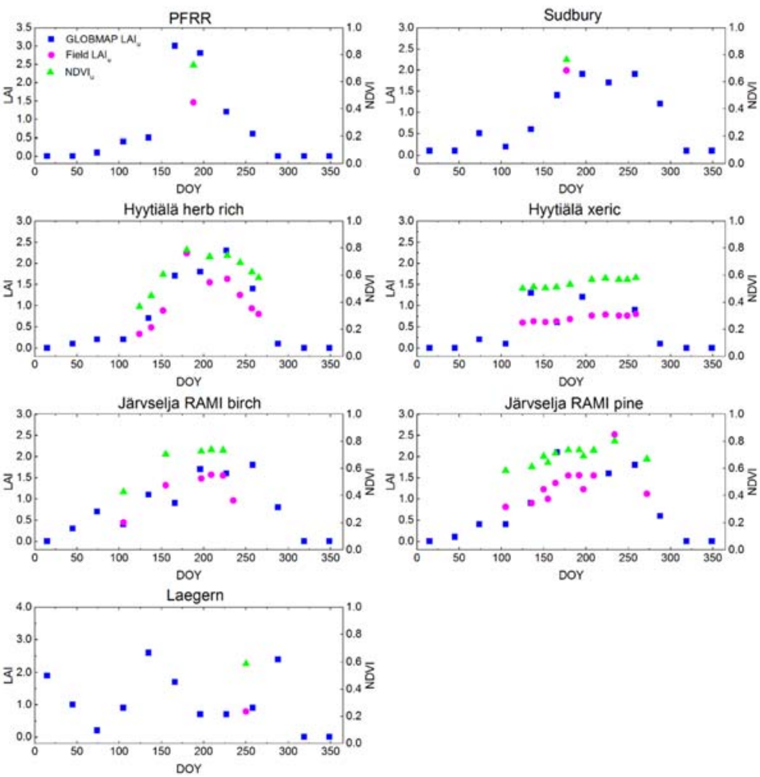


Figure ~~13~~10. Seasonal profiles of GLOBMAP LAI$_u$ (blue) and their comparison with in situ understory NDVI (NDVI$_u$, green) measurements and estimated understory LAI from field NDVI$_u$ (Field LAI$_u$, pink) in seven forest sites, including stands in PFRR, Sudbury, Hyytiälä herb rich, Hyytiälä xeric, Järvselja RAMI birch, Järvselja RAMI pine and Laegern.

Hyytiälä Herb Rich (61.84° N, 24.32° E) and Hyytiälä Xeric (61.81° N, 24.33° E) are two southern boreal forest stations with dominant tree species of birches and Scots pine, respectively. The former is more fertile than the latter. Understory vegetation is dominated by herbaceous species and graminoids at the herb-rich site, while lichens and heather at the xeric heath forest. At the Hyytiälä Herb Rich site, the GLOBMAP LAI$_u$ captures the seasonal curves represented by field NDVI$_u$, and the values are consistent well with estimated field LAI$_u$, with the LAI$_u$ reaches approximately 2.0 in the summer. In contrast, at the Hyytiälä Xeric site, the LAI$_u$ shows smaller variations with the values below 1.5 in the summer.

For the two hemiboreal forests sites Järvselja RAMI birch (58.28° N, 27.33° E) and RAMI pine (58.31° N, 27.30° E), the geolocations are more southern, and the understory vegetation is more abundant and host more species than in boreal Hyytiälä. The GLOBMAP LAI_u increases earlier and the values are still above 0.5 in October in the more southern Järvselja sites. As the complexity of the understory enhances the challenge of understory LAI retrieval, the seasonal series are not as smooth as that in Hyytiälä. Even so, the GLOBMAP LAI_u could capture the understory development in the spring and senescence in the fall, and its values are generally close to the estimated field LAI_u.

The Laegern site in Switzerland represents a temperate mixed forest. The overstory is dominated by very big European beech and Norway spruce, with effective LAI up to 5.5, mean tree height of 30.6 m and max crown radius greater than 10 m (see details in Pisek et al., 2016). The understory vegetation is sparse and consists mainly of *Allium ursinum*. Although the GLOBMAP LAI_u in September (0.9) is very close to the estimated field LAI_u in DOY 250, its time series does not appear stable during the whole year. This suggests that large uncertainties may exist in the retrieved understory and overstory LAI for such dense and closed canopy ~~where the dominant scattering effect is shadowing~~which make it difficult to observe the signals from understory on the top of canopy, which has also been pointed out~~proved~~ by Pisek et al. (2016).

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3.7 Seasonal effects of the background reflectivity on the LAI retrieval

The GLOBMAP LAI_T was generated by summing LAI_o and LAI_u in the same month, and the mean differences between the GLOBCARBON LAI and the GLOBMAP LAI_T and LAI_o (GLOBCARBON LAI minus GLOBMAP LAI_T/LAI_o) were calculated over the global forest area from 2008 to 2010 to evaluate the effects of monthly pixel-specific forest background reflectivity on forest LAI retrieval.

Figure 11 shows maps of the difference between the GLOBCARBON LAI and the GLOBMAP LAI_T as well as LAI_o over the global forest area. The difference between the GLOBCARBON LAI and the GLOBMAP LAI_T is negative for most forest pixels. This is probably because some forest understory effects have been considered in the GLOBCARBON LAI by using the constant background SR value of 2.4 (Deng et al., 2006), while the GLOBMAP LAI_T includes the LAI for all forest canopy and understory vegetation. This difference is small for needleleaf forests, with a yearly mean difference of -0.48 for ENFs and -0.59 for DNFs, while the difference is larger for DBFs (-0.68). This suggests that the standard background SR in the GLOBCARBON LAI algorithm is more suitable for boreal forests, which is probably because the standard background SR value (2.4) is based on field measurements in boreal forests in Canada (Chen et al., 2002). In contrast, the difference between the GLOBCARBON LAI and the GLOBMAP LAI_o is positive for most forest pixels, which is attributed to the partial signals of understory still included in the GLOBCARBON LAI. Because the difference mainly represents signals from the forest understory, it is also larger for needleleaf forests than broadleaf forests due to their more clumped foliage, especially in the boreal forest zones (Fig. 11b), with yearly mean differences of 0.62 for ENFs, 0.43 for DNFs and 0.35 for DBFs. Figure 12 shows monthly mean differences and STD series in the northern hemisphere. Notable seasonal variations are also found for the three forest types (Fig. 12b). The two difference are both large in the summer. For the difference between the GLOBCARBON LAI and the GLOBMAP LAI_T, it ranges from 0.0 to -0.5 from November to April, while with values of up to -0.8 for ENFs, -1.3 for DNFs and DBFs in July and August. For the difference between the GLOBCARBON LAI and the GLOBMAP LAI_O, it is smaller from November to April with a mean difference within 0.4, while it is larger for needleleaf forests during the summer, with mean differences up to approximately 1.0 for ENFs, 0.8 for DNFs and 0.4 for DBFs from June to August.

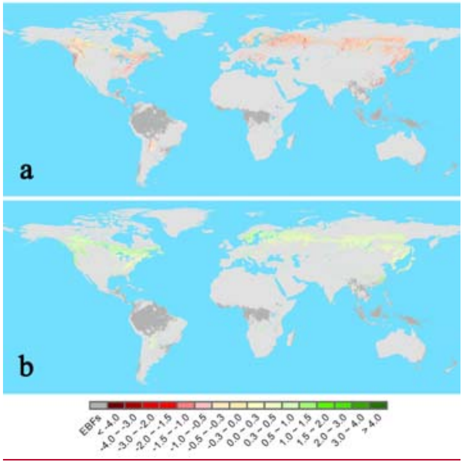

Figure 11. Maps of the differences (GLOBCARBON minus GLOBMAP) between (a) the GLOBCARBON LAI and the GLOBMAP forest total LAI (sum of the overstory and understory LAI) and (b) the GLOBCARBON LAI and the GLOBMAP forest overstory LAI. The results for the EBFs are excluded.

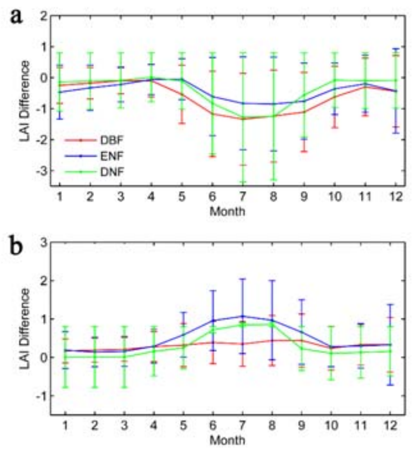

Figure 12. Monthly mean differences between (a) the GLOBCARBON LAI and the GLOBMAP LAI_T (sum of the overstory and understory LAI) and (b) the GLOBCARBON LAI and the GLOBMAP LAI_o over the global forest area in the northern hemisphere based on data from 2008 to 2010.

The forest understory vegetation and soil background vary with forest type, site and season. Notable uncertainties would be introduced if a constant background were used in the LAI retrieval. The GLOBCARBON LAI products remove partial effects of the forest background, leading to the differences between the GLOBCARBON LAI products and the GLOBMAP LAI_T as well as the LAI_o. These differences vary with the forest type, geographic location and season. Due to the different roles of the overstory and understory layers, uncertainties will be introduced into the estimation of the forest water and carbon cycle (Chen et al., 1999). This problem also exists for other LAI products, which do not separate these two layers for forests. Pixel-specific seasonal forest background reflectivity helps to account for the effects of the forest background on the LAI retrieval.

4 Discussion

Many factors affect the quality of the derived forest overstory and understory LAI, such as LAI algorithm and inputs, mainly including MOD09A1 land surface reflectance, MISR forest background reflectance and clumping index. The MISR forest background reflectivity was used to estimate the forest understory LAI directly and correct for the effects of the background in the MODIS observations before the retrieval of the overstory LAI. Thus, the uncertainties in the MISR forest background reflectivity will be ~~introduced~~ propagated into the results. It is pointed out that the tree architectural parameters used in 4-scale model and the land cover may affect the retrieved forest background reflectivity (Jiao et al., 2014), which will also affect the derived forest overstory and understory LAI. Additionally, the overstory and understory true LAI was converted from effective LAI retrievals with the global clumping index map derived from the MODIS BRDF product (He et al., 2012). The ~~Q~~quality of this clumping index map would also affect our results.

The reliability of the retrieved LAI is different for various forest types and seasons. Generally, it is difficult for satellite sensors to capture signals of the understory through the dense canopies. The reflectivities of the forest background tend to be unrealistic for dense canopies with LAI greater than 4, so the understory LAI is more reliable for sparse forest, and the retrievals in the spring and autumn should be more reliable than those in the summer. In addition, it is easier for optical remote sensing to capture signals from understory vegetation for coniferous forests than for broadleaf forests due to the more clumped foliage of the needleleaf forests. In fact, the structure of forest is very complicated. The overstory and understory may be composed of several sublayers, and the young forests' canopy may be even continuous from ground to canopy-top. In order to characterize the forest vertical structure from remote sensing data at global scale, forest is simplified to two layers, i.e. overstory and understory layers. Specifically, for EBFs, its vegetation structure is much more complex than any other forest type, making it difficult to clearly separate the canopy into overstory and understory. Besides, in the forest background reflectivity algorithm, EBFs share tree architectural parameters (such as stand density, tree height and tree stem diameter) with DBFs, which may introduce significant uncertainties into the background reflectivity in the tropical zones due to large differences between these two forest types. To avoid the influence of unconvincing forest background reflectivity, the EBFs were excluded in this study.

Forest understory has usually large species variation and heterogeneous spatial distribution. Besides, it is not entirely independent from the tree canopy since changes in canopy closure or tree layer LAI will lead to a change in the species composition and green LAI of ground vegetation (Rautianinen and Heiskanen, 2013). Generally, although the composition of understory is complex and site-dependent, the typical species are shrubs, grasses and other herbaceous plants, mosses and lichens (e.g., Deering et al., 1999; Maeno and Hiura, 2000; Peltoniemi et al., 2005; Liang et al., 2012; Ryu et al., 2014; Qi et al., 2014; Nikopensius et al., 2015). In this paper, the understory LAI is estimated by averaging the retrievals based on GLOBCARBON LAI algorithm for shrubs and grasses/crop/other non-forest vegetation. Thus, the complicated understory composition is simplified as shrubs and non-forest non-shrub vegetation. The retrieved understory LAI may be affected by the uncertainties of GLOBCABRON LAI algorithm for non-forest biomes. In addition, this simplification will also introduce uncertainties if the composition were not half shrubs and half other non-forest vegetation. Fortunately, the retrievals based on the algorithms for these two biomes are not quite different (Sect. 3.1). Therefore, this simplification enables us to characterize the vertical structures for global forest from optical remote sensing observations. Moreover, Lidar provides another powerful tool for monitoring forest vertical structures. For example, GLAS spaceborne waveform lidar data has been used to extract forest vertical foliage profile over the United States at the footprint level (Tang et al., 2016). A ~~C~~combination of Lidar and optical remote sensing may improve the forest structure monitoring.

It takes 9 days for MISR to acquire global coverage due to its relative narrow swath width of approximately 360 km. With influences of this low temporal resolution~~ and~~, occurrence of clouds, topographic obscuration and failed aerosol retrievals, large proportion of missing data and invalid retrievals is ~~presented~~ included in the MISR ~~daily~~ Land Surface Products (Liu et al., 2012b). As a result, there are large numbers of invalid retrievals in the ~~daily~~ MISR forest background reflectivity ~~derived from MISR observations~~ (Jiao et al., 2014). To generate spatially coherent maps, we have to compose the monthly forest understory LAI using the ~~daily~~ retrieved results during the 11-year period from 2000 to 2010. Thus, the changes in the forest understory among years and within month are not considered in this paper, such as fire and other disturbance. Recently, the background reflectivity has been retrieved from MODIS BRDF products with a temporal resolution of 8 days over selected sites (Pisek et al., 2012; 2016). Such BRDF products have high temporal resolutions, and should make it possible to account for the inter-annual and seasonal variations in the forest understory vegetation in the future.

5 Conclusions

In this paper, the forest LAI is separated into overstory and understory layers over the global deciduous broadleaf and needleleaf forest areas based on monthly 1-km MISR forest background reflectivity and MODIS land surface reflectance. The global monthly 1-km forest understory LAI (GLOBMAP LAI_u) and 8-day 500-m forest overstory LAI (GLOBMAP LAI_o) were retrieved.

Forest overstory is the dominant component of forest LAI, and its spatial and seasonal patterns are close to those of the forest total LAI. The forest understory is mainly found in the boreal forest zones in the northern latitudes (~~40~~50° to 70°N), where 84% of ~~global~~ valid LAI_u retrievals are found in July. Significant seasonal variations of the LAI_u are present in this region, with LAI up to 2-3 from June to August. Needleleaf forests have more high values of LAI_u than broadleaf forests, and its mean value (1.06 for ENFs and 1.04 for DNFs) is also larger than those for DBFs (0.96) due to its more clumped foliage. The mean proportion of understory LAI to total LAI is greater than 30% (36% for DBFs, 34% for DNFs and 31% for ENFs), indicating that the effects of forest understory cannot be ignored in canopy parameters estimation and forest carbon cycle modeling. ~~As a result of the differences in geographic distribution, climate and vegetation composition, the seasonal LAI_o and LAI_u curves change for various forest types. For forest overstory, the magnitude of seasonal variations is larger for DBFs than those of DNFs and ENFs. In contrast, for forest understory, needleleaf forests show larger seasonal variations than broadleaf forests, with higher LAI_u values in the summer. The retrieved LAI_o and LAI_u values were compared with the Kobayashi datasets, which were derived from SPOT/VGT observations based on three-dimensional radiative transfer simulations for larch forests in eastern Siberia. The mean GLOBMAP LAI_u (0.48) and LAI_o (1.95) are close to that of Kobayashi LAI_u (0.42) and Kobayashi LAI_o (1.61), leading to an absolute error of 0.06 (0.34), relative error of 14.3% (21.1%) and RMSE of 0.29 (0.93). The LAI_u and LAI_o were also validated against field measurements. The R^2 is 0.62 and 0.52, and the RMSE is 0.62 and 1.36 for understory and overstory LAI, respectively. And the derived LAI_u is consistent well with field understory NDVI measurements and estimated understory LAI over different forest types.~~ The retrieved results show better consistency with the ground data for forest with lower LAI, while it is hard to separate the understory signal from the overstory for dense and closed canopies.

~~The forest understory vegetation and soil background vary with forest type, geographic location and season. Uncertainties would be introduced if constant forest backgrounds were employed in the estimation of the forest LAI, as in the GLOBCARBON LAI. Comparison between the GLOBMAP LAI_T and the GLOBCARBON LAI shows significant variations in the difference between these two LAI dataset among forest types and seasons. The difference is smaller for needleleaf forests than broadleaf forests, with a yearly mean difference of -0.48 for ENFs, -0.59 for DNFs and -0.68 for DBFs, which is probably because the constant forest background SR value was estimated from field measurements of boreal forests in Canada. The difference is smaller from November to April (-0.5~0) than in the summer (up to -0.8 for ENFs, -1.3 for DNFs and DBFs in July and August).~~

~~It is challenging to separate the LAI for forest canopy and understory vegetation at the global scale. In this paper, with the aid of forest background reflectivity derived from MISR multi-angle observations, we try to separate forest overstory and understory LAI over the global needleleaf and DBFs areas with a spatial resolution of 1 km.~~ Although uncertainties still exist due to the many factors discussed above, this work would help us better understand the seasonal patterns of forest structure, distinguish different responses of forest overstory and understory to climate change, evaluate the ecosystem functions and improve the modelling of the forest carbon and water cycles. It is difficult to validate the forest understory and overstory LAI directly due to the lack of field measurements with separation of vertical layers, especially of understory LAI. Further studies of the structural characteristics of the forests and use of field lidar are necessary to evaluate the remote sensing overstory and understory LAI datasets.

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