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Biogeosciences Discussions

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9, C9331–C9344, 2013

Interactive Comment

Interactive comment on "Remote sensing of LAI, chlorophyll and leaf nitrogen pools of crop- and grasslands in five European landscapes" *by* E. Boegh et al.

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We appreciate very much the thorough review given by the anonymous referee. It has been very valuable to clarify objectives and remove some misunderstandings and to improve the analysis and presentation of results. In particular, the paper has been restructured to clearly separate results and discussions related to the two objectives of the paper since we found that this provided the basis for some misunderstandings; more emphasis is given to the presentation and analysis of REGFLEC results, and uncertainty assessment of field data is now considered.

Please find detailed replies to the comments below.

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Interactive Discussion

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REFEREE # 1 General comments

The paper stems from the activities of a large European project and has the objective of assessing the utility of remotely sensed LAI and leaf chlorophyll and nitrogen (N) estimation methods using data collected in 5 sites, mostly located in Northern Europe (with the exception of an Italian site). A second objective was that of assessing the distribution and size of vegetation N pools in the 5 sites. My overall impression is that the data and the methods employed did not allow to answer satisfactorily to such rather different objectives. For the first objective, not particularly original since dozens of papers have been written on this topic,

- REPLY - 1) Only a few papers assessed the performance of remote sensing based methods for estimating vegetation properties over such a large range of environmental conditions as in this paper, and those that did this used low spatial resolution data (1000 m) such as MODIS or ENVISAT where it is difficult to achieve ground-truth data at an adequate spatial resolution. In this study, high spatial resolution remote sensing data are used to represent homogeneous field plots in 5 diverse environments (landscapes) located within a larger region, and a thorough field sampling were conducted that included leaf sampling at 5 canopy height levels in 93 field plots. The measurements at 5 height levels were originally designed in order to analyze the remote sensing performance for CHL and N estimation using field data representing the bulk canopy and the upper canopy levels, respectively. It turned out that the best remote sensing performance was achieved when canopies with strong CHL profiles were excluded from the evaluation. No paper previously considered the impact of vertical chlorophyll variation on the performance of remote sensing based methods for estimating vegetation properties.

- 2) It is true that a dozen of papers have been written on remote sensing of LAI, chlorophyll and leaf nitrogen (but not many considered all three variables in one paper). We considered changing the title of the paper to better reflect the research contribution of the paper, but we believe that the reference to application in “five European land-

BGD
9, C9331–C9344, 2013

scapes" in the current title reflects well the challenges and contribution of the research. The approach taken to evaluate the capability of high spatial resolution remote sensing estimates over such a large range of environmental conditions is not normally done.

a more thorough sampling and an independent validation should have been performed.

REPLY - 3) It is believed that the Referee refers to the fact that the empirical relationships between SVIs and field data were established using all available field data. The original purpose of the paper was to assess the performance of REGFLEC over a large range of environments including different soil backgrounds, atmospheres and land uses. But REGFLEC did not perform as well as expected (not as good as in other studies, probably due to lack of soil maps and a lack of local data for atmospheric corrections, as discussed in paper). Therefore, a number of well-established and recent promising SVIs were also included. The purpose was to assess the performance of REGFLEC in relation to SVIs which are known to be closely related to vegetation properties. The statistical significant correlations between SVIs and (in particular) LAI also works to verify the quality of field data in cases where the REGFLEC approach did not agree with field observations. For instance, it was found that REGFLEC did not perform well in Italy due to a lack of dense vegetation canopies at the time of satellite recording. Presence of dense fields is needed for each land use type in order to parameterize the canopy radiative transfer model used by REGFLEC. In contrast, the SR-vegetation index (and others) was closely related to field measurements in Italy, thereby verifying field data quality as well as the utility of empirical SVI approaches which are however data-dependent methods. It was also confirmed that EVI2 is superior in densely vegetated landscapes (in agreement with its theoretical basis), and it was found that REGFLEC worked best in landscapes comprising a large range of vegetation covers (sparse to dense). In the revised paper, there is a larger focus on REGFLEC performance (please see reply 5).

More emphasis should have been given to the intrinsic difference between empirical (SVIs) and more general (and innovative) physically-based model inversion methods

BGD
9, C9331–C9344, 2013

Interactive Comment

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Interactive Discussion

Discussion Paper

such as REGFLEC.

REPLY - 4) The presentation of REGFLEC has been extended. References are also given to 4 scientific papers which are presenting the model in further detail, and a reference is given to the model homepage, www.regflec.com where more information can be found, and the REGFLEC model can also be downloaded.

- 5) Based on the referees' comment, the (first) objective of the paper now focuses on evaluating REGFLEC performance, and the use of SVIs is better explained (please see reply # 3). For the second objective, both REGFLEC and SVIs are used for landscape based N assessments.

Moreover more attention should have been given to the uncertainties and errors inherent in "ground truth" data which were essentially indirect estimates of the target variables.

REPLY - 6) Ground-truth data of LAI were acquired using the LAI-2000 instrument (Licor Inc, USA) which is a common method for deriving LAI, however based on optical measurements rather than destructive field measurements. In Boegh et al. (2004), LAI-2000 measurements were compared with destructively sampled LAI estimates for maize, wheat, grass and barley throughout the growing season, and it is clearly seen that there is a very good agreement between the two estimates until the senescent phase starts. A reference to this study has been included.

- 7) The SPAD meter is another standard spectral measurement technique for estimating chlorophyll and leaf nitrogen. References have been included for documentation of this technique. Empirical correlations between measured SPAD meter indices, leaf chlorophyll and leaf nitrogen measurements were already shown in the paper. The advantage of using SPAD meter measurements and LAI-2000 are that many measurements can be made in a short time.

The results are perhaps presented too optimistically, since the best of the different

BGD

9, C9331–C9344, 2013

approaches were combined excluding (admittedly) data with vertical gradient profiles, which are perhaps more common than it was found in this paper.

- REPLY - 8) In fact, REGFLEC performance was poorer than in previous studies (as reported in the paper), however we recommend that future REGFLEC studies should include a remote sensing scene showing bare or sparsely vegetated soils in order to facilitate model parameterization of soil background reflectance (this has been done in some previous REGFLEC studies). We also found that REGFLEC did not perform well in Italy due to the lack of dense fields (needed for model parameterization) or perhaps due to the predominance of broadly spaced row-cropped fields which is not represented by the canopy radiative transfer model. This is already discussed in the paper.

However, Fig. 6 shows results which are based on different approaches. We realize that this way of presenting overall results may be misinterpreted as a validation test for the remote sensing capability. Since the results shown in Fig. 6 are based on combining different methods, this would be quite misleading. Therefore, the correlation coefficients have been removed from Fig. 6, and the calculation and discussion of Model Efficiency (ME) has also been removed. The original purpose of providing the correlation coefficients and ME was to quantify the degree of confidence with which N could be mapped in the landscapes. In the revised version of the paper, results and discussions related to the two objectives of the paper are clearly separated in two subsections. The first section discusses objective 1 which is “to assess the capability of selected remote sensing methods to quantify LAI, CHL and N over a large range of environmental conditions” (main results in Tables 4 and 5, now also visualized graphically), and the second objective, discussed in section 2, is “to assess the distribution and size of vegetation N pools in the five European agricultural landscapes” (results in Fig.’s 6, 7 and 8).

- It is already mentioned in the paper that many canopies had a bell-shaped or S-shaped chlorophyll profile. In this study we chose to work with a criterium (which can

BGD

9, C9331–C9344, 2013

easily be replicated and tested by others) to remove canopies with strong (negative or positive) chlorophyll profiles. This means that canopies with bell-shaped chlorophyll profiles are included in our data representing “uniform” canopies. It is possible that other criteria could also be used, however many attempts were already done (not shown in paper) to assess remote sensing results using different criteria and different leaf-scale data averaging techniques. We found that the best results were obtained after removal of field samples characterized by strong chlorophyll profiles.

For the second objective, in my opinion the data did not cover an adequate spatial and temporal extent (being just a snapshot) to allow a substantiate explanation of the differences among the landscapes in terms of vegetation N pools. In this respect it should be paid more attention to the fact that the comparison between sites is much less straightforward than it would have been with natural vegetation, since crops with different growing cycles are present in the sites.

REPLY - 9) It is already explained in the paper that the landscape N pools are related to seasonal variations, agricultural land use, species etc, and we clearly agree with the Referee that the results do not allow a substantiate explanation of the differences among the landscapes, being just snapshots. On the other hand, how can this ever be obtained, if not by remote sensing? The remote sensing estimates in this study do in most cases provide significant statistical results allowing the upscaling of field measurements to landscape scale, and in some cases, the remote sensing based landscape estimates vary greatly from the averaged field data. To our opinion, these results do demonstrate the important potential of remote sensing to contribute to landscape-scale carbon and nitrogen cycle research. In the revised paper, we added information that more satellite data (time-series) would be required to give a substantial substantiate assessment of differences between landscapes.

Specific & minor points (reference is made to page P and line L numbers):

Title: actually canopy and not leaf Chl and N were predicted, thus probably the title should be changed accordingly.

REPLY - 10) The title refers to “LAI, chlorophyll and leaf nitrogen pools” in order not to confuse with the bulk nitrogen content of canopies which includes other plant organs than leaves. If the term “canopy nitrogen” content is used, we expect that it could cause some confusion since the Chl and N contents of stems etc are not considered. We are open to other suggestions.

P10151 L6: "...data and are not verified...."

- REPLY - 11) The sentence has been removed

P10151 L26: here and later on in the Discussion, I would not use the expression "further improved", since in one case single land use categories (i.e. crops!) were used and in the other single sites but different "land use categories", a rather different way of looking at results.

REPLY - 12) Agree! These sentences have been reformulated.

P10152 L15-19: I don’t grasp the logic of this sentence beginning with "Despite"...

REPLY - 13) Admitted. The sentence has been shortened and simplified. Thank you.

P10153 L11: I would call them variables rather than products.

REPLY - 14) It has been changed, as suggested.

P10157 L4- P10158 L20: I don’t understand why the names of the sites and their geographic coordinates and altitudes are omitted.

REPLY - 15) An agreement was made with farmers in each of the NitroEurope landscapes to do measurements in their fields, provided the data are presented without the exact geographic references in order to ensure farmers anonymity. The geographic coordinates and mean elevation of each landscape are seen in Table 1. Furthermore, it is decided to upload all field data and the extracted remote sensing data as supplementary material. The SPOT reflectance data will include both mean and variance for the field sites and for the complete field.

P10159 L21-22: Here is in my opinion one of the major weaknesses of the paper: inadequate sampling. The authors should better explain how the 3x3 m areas were placed within the 10x10 m areas and justify the representativeness of these areas in terms of SPOT satellite pixel sizes and georeferncing error (typically one pixel or more...).

REPLY - 16) In contrast to plot-scale remote sensing studies, the field sites were not demarcated because we were only in the field once (close to the time of satellite passage), and we did not plan to return to the same site to do additional (time series) measurements. Instead, the purpose was to conduct LAI and SPAD meter measurements in a number of different fields using 1-2 days of fieldwork in each landscape. The size of the field plots was defined by the LAI-transect which was set to be 3 m (using 4 light transmission measurements). Replicate LAI and GPS measurements were done in two neighbouring areas to increase confidence that the vegetation density was homogeneous in the $\approx$ 10 x 10 m2 region. SPAD meter measurements were made in affinity to LAI transects.

- Field measurements were deliberately done in homogenous fields only (first based on visual assessment in the field; then by measuring LAI 2-4 times), however the UK grassland sites were more heterogeneous. In order to document homogeneity of the fields, the SPOT (satellite) spectral reflectance variance was calculated for each 3x3 pixel block centered at the georeferenced (10 x 10 m2) field site, and the spectral reflectance mean and variance were also calculated for the entire fields. The calculations are included in the uploaded supplementary data file and reported in the revised paper.

- SPOT georeferencing error was assessed by overlaying the satellite images by ESRI's Streetmap Premium Europe Tele Atlas data set (the streetmap is also used as a mask with buffer zones of 1 pixel – please see Fig. 7). Minor deviations were found in some cases which could be adjusted by shifting the image coordinates slightly in the X-Y directions. This minor X/Y-adjustment is now described in the paper. Geographic coordinates were measured in each field plot with an accuracy of 0.5 m, as explained in the paper.

- We believe that the field sampling is already clearly described but have inserted a few words (seen in red) in red to clarify further. As explained in the paper, “Each field plot is represented by two sub-areas of 3 x 3 m2 located within a 10 x 10 m2 region of the field.” “...with each 10 x 10 m2 field plot being geographically referenced with an accuracy of 0.5 m using GPS (Trimble Geo XT, Trimble, USA)”. “LAI was measured with the LAI-2000 instrument (LAI-2000, LiCor, USA) which uses canopy transmission data measured along a transect. Replicate LAI estimation was made in the two neighbouring plots, with each LAI estimate being based on 4 light transmission measurements along a 3 m transect. If the LAI estimates of the 2 transects varied, a third transect (a third plot) was included. In most cases, LAI variation was very low, but in a few cases at the grassland sites in NL, up to 4 transects were included due to high spatial data variability. In these fields, the average LAI is used to represent the field plot.”

- All field data and remote sensing data will be uploaded as supplementary data

P10159 L24 - P10160 L6: the authors should acknowledge that LAI-2000 data are indirect estimates of LAI, representing more properly "effective" (i.e. not accounting for clumping) PAI (plant area index), i.e. not differentiating between leaves and other plant organs. Here the sampling scheme is reported to follow transects: how do they relate to the 3x3 areas mentioned before? One or two transects with 4 measurement points in a 3x3 area? Are you sure that the number of points was enough? What could be the error and uncertainty in the estimated "ground truth" LAI value?

REPLY - 17) A reference (Boegh et al., 2004) has been included which shows that LAI-2000 measurements are very efficient (sometimes clearly better than destructive measurements) at representing the true LAI in the vegetative period, but that the LAI-

BGD
9, C9331–C9344, 2013

2000 and destructive LAI measurements deviate in the senescent period where the presence of other plant organs causes the LAI-2000 measurements to overestimate LAI. In the current study, the field campaigns took place early in the growth seasons (Table 1), and it can be expected that the LAI-2000 measurements closely represent the actual LAI.

- Two LAI transects of each 3 m are used, as explained above and in the paper. The reason for doing replicate transect measurements was to assess LAI variability. Based on the 2-4 sets of LAI estimates in each field, the averaged relative uncertainty (sd/mean) is 10 %, except for the UK grassland fields where LAI is generally very low and uncertainty is higher (average 35 %). This is now reported in the paper, and we propose to upload the data as supplementary material.

- Remote sensing based variance of the spectral reflectance (3x3 pixels centered at the georeferenced field site and variance for the complete field) were calculated, reported and will be uploaded as supplementary data to further document field data homogeneity.

P10160 L28: something wrong here since in the paper by Porra et al. (1989) equations for other solvents (methanol, NN-DMF) but not ethanol are reported.

REPLY 18) Thank you very much. The reference has been corrected. We used Porra et al. (1989) earlier, but in this study, ethanol was used for chlorophyll extraction using coefficients from Lichtenthaler, H.K. (1987). Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes. Methods in Enzymology 148: 350-382.

P10161 L9: it would be useful to report the equation best fitting all data (e.g. to allow comparison with other calibrations reported in the literature).

- REPLY - 19) We believe that field data are always needed to calibrate SVIs, however the equations are now reported in an appendix (Referee # 2 also asked for these equations) - P10161 L13: Houborg and Boegh 2008 is not in the references.

- REPLY - 20) Thank you. References have been included

P10161 L23: you should report exactly how you computed canopy chlorophyll and N. What could be the uncertainty of these estimated "ground truth" variables?

- REPLY - 21) Canopy chlorophyll and canopy nitrogen are computed simply by multiplication of averaged leaf scale measurements and LAI, ie CHLc = LAI âĂć CHLl where CHLl is the mean leaf chlorophyll concentration. Different ways of averaging leaf chlorophyll and leaf nitrogen measurements were tried (ie using only data from upper 2 or 3 measurement levels) in order to study the resulting relationships between field data and remote sensing estimates, however the final estimates applied in this study are based on averaging all leaf scale data. This is now clearly described in the paper.

- Since the variation in leaf chlorophyll with height is not (all) due to measurement uncertainty (due to vertical chlorophyll data structure), it is not possible to simply use the standard deviation (SD) of all leaf-scale measurements to assess data uncertainty. Instead, we may consider each measurement level as a separate sample and then express mean leaf chlorophyll concentration as

CHLl = 0.2 (CHLl(20) + CHLl(40) + CHLl(60) + CHLl(80) + CHLl(100))

where CHLl(20) represents all leaf chlorophyll measurements at the “20 % relative height level” within one field etc. The absolute uncertainty (au) for CHLl can then be assessed as

CHLl_au = 0.2 âĂć sqrt(SD20ˆ2 + SD40ˆ2 + SD60ˆ2 + SD80ˆ2 + SD100ˆ2)

and the relative uncertainty is then CHLl_ru = CHLl_au/CHLl.

The relative uncertainty in a product such as “ CHLc = CHLl âĂćLAI “ is simply the square root of the sum of squares of the relative errors in LAI and CHLl:

CHLc_ru = sqrt(CHLl_ruˆ2 + LAI_ruˆ2)

Using these expressions, it is found that relative uncertainty for mean chlorophyll concentration (CHLl) varies between 2 % and 25 % (median is 8 %). Assuming relative uncertainty for LAI is $\approx$ 10 % (please see reply 17), relative uncertainties in canopy chlorophyll (CHLc_ru) would be roughly in the range 10-25 % (median $\approx$ 13 %).

In the revised paper, the uncertainties for canopy chlorophyll and N are calculated in the way described here.

P10164 L24-18: the description of the REGFLEC algorithm is not clear. I understand that it should be synthetic, but I had to read the references to figure out how it works!

- REPLY - 22) The description of REGFLEC has been extended, and a reference to the REGFLEC homepage is inserted (www.regflec.com)

P10165 L23 and further on: the comparison between vegetation status among sites would have made more sense for natural vegetation, or in case you had the same crop in all sites, but here you have crops with different sowing and harvest dates...

- REPLY - 23) Yes, but this is how agricultural landscapes vary on larger scales, and we would like remote sensing methods to be applicable to such landscapes. We agree that it could be very interesting to apply the methods for a variety of landscapes representing natural vegetation. The remote sensing based landscape-scale estimates are however found to be a valuable contribution to field based estimates of leaf nitrogen pools. - P10169 L3-L11: actually in many cases the vertical chlorophyll concentration profile has a bell-shaped form (e.g. Winterhalter et al., 2012; Ciganda et al., 2012, Remote Sens. Environ. 126:240-247) that could possibly result in a non significant linear regression. So the criteria used to differentiate between poor and strong vertical structure seem too simplistic to me, leading perhaps to an underestimation of the canopies having "strong" vertical profile (only 20%).

- REPLY - 24) Yes, many canopies have bell-shaped or S-shaped chlorophyll profiles, as noted in section 4.3. These canopies are included in our validation data represent-

BGD

9, C9331–C9344, 2013

Interactive Comment

ing “uniform” canopies. From visual inspection, the applied criteria works to remove canopies with strong (negative or positive) chlorophyll profiles (as explained in the paper). A decision on a criteria is necessary to avoid subjective sorting of data. It could be that they do not pose a large problem, or that they can be post-processed to facilitate better agreement with remote sensing data, but this may be investigated further in future. It is proposed to upload all data as supplementary material for free access.

P10169 L25-L27: probably the major weakness of this paper (or at least one of the least clear points) is in the "validation" of the estimates of LAI (and other variables). It seems as if validation was not independent from calibration: i.e. did you develop statistical models for SVIs and then used them on an independent data set or not? In the latter case these are not actual LAI "predictions" to compare with "measured" LAI.

- REPLY - 25) The REGFLEC model is not calibrated, but all SVIs are calibrated, and we believe that calibration of SVIs will always be needed to take account of local environmental conditions. We did not use independent data to validate the SVIs. Many other studies gave empirical evidence for close relationships between SVIs and vegetation properties (in fact, it is common to use all data for this purpose). However, we find it is interesting that these relationships in many cases perform better when canopies with strong chlorophyll profiles are removed from the data.

P10170 L11: a citation is needed here.

- REPLY - 26) References have been included to four REGFLEC papers at this place.

P10172 L10: actually in Table 5 GNDVI for CHLc seems significant for PL.

- REPLY - 27) Yes, it is significant for PL (therefore bold), and better than all the other methods for CHLc in PL (therefore cursive)

P10172 L25: table 3 rather than Fig.2.

- REPLY - 28) Thank you. It has been corrected.

BGD

9, C9331–C9344, 2013

Interactive Comment

P10175 L24: how could the selection of only those canopies without vertical gradient profiles could affect the generalization of the estimation methods proposed to the regional scale, e.g. from an operative point of view? - REPLY - 29) The possible impact of chlorophyll variability in canopies should be considered when assessing the capability of remote sensing methods for chlorophyll, N and LAI estimation. Thus, we find that it is important to consider vertical chlorophyll variability when sampling data for evaluation of remote sensing methods. This viewpoint is clearly communicated in the revised paper.

P1017 L19 : Houborg et al 2007 and Houborg and Boegh 2008 not in the references.

- REPLY - 30) They have been included. Thank you.

Interactive comment on Biogeosciences Discuss., 9, 10149, 2012.

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