Interactive comment on "Regional detection of canopy nitrogen in Mediterranean forests using the spaceborne MERIS Terrestrial Chlorophyll Index" by Yasmina Loozen et al.

Anonymous Referee #1

Received and published: 5 September 2017

We would like to thank the reviewer for reviewing our manuscript.

The manuscript shows an interesting study on the use of MERIS data to analyze empirical relationships between MTCI and ground measurements of forest canopy N content and concentration. Foliar N influences a variety of important ecosystem processes so it is clear the interest of exploring the capacity for remote detection of canopy N at regional scales from space-based platforms and the potential of new generation of sensors such as those included in the Copernicus program. However, direct estimation of N in fresh vegetation using remote sensing data is challenging due to its weak effect on leaf reflectance so the influence of structural properties of the canopy and other potential confounding factors related with the input data are key issues to be explored.

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The paper is well written and also well-structured and the research questions addressed are relevant and clearly fall within the scope of Biogeosciences.

Thank you for your nice comment.

However, my main concern about this work is that, at some point, the paper could be read as a search for correlations without a thoughtful discussion on the different **confounding factors** that could potentially affect to the observed relationship between satellite and ground data and how these factors could impact the results.

We understand your concern about this paper being a search for correlations and would like to stress that we did a directed search rather than a random search. Remote sensing of canopy N (especially handheld and airborne) has already been extensively investigated and vegetation indices based on the red-edge region, on which MTCI is based, have been repeatedly used (Schlemmer et al., 2013;Li et al., 2014;Cho et al., 2013;Clevers and Gitelson, 2013;Dash and Curran, 2004). In this study, we want to extend on the existing analyses by including spaceborne remote sensing. We will explain this in the introduction part of the manuscript. Next, we will also address the possible confounding factors and their effects on the MTCI canopy N relationship in the discussion part of the manuscript. The potential confounding factors include e.g. biomass, canopy structure, LAI, as well as geomorphological variables (Sardans et al., 2011;Sardans et al., 2016).

A key element in this study is related with the intrinsic limitations of the input data: spatial (1) and temporal mismatch (2) but also, for example, the method used to scale from leaf to canopy N using field sampling strategies (3).

1) The reviewer is correct, since the beginning of this project we were aware of the limitation of the dataset included. We chose to use the data from the Catalonia National Forest Inventory because it includes many plots that are well spread over the forested region of Catalonia. The spatial mismatch has been addressed by resampling both the MTCI product and the canopy N ground measurements to the same and lower spatial resolution. Then, we analyzed the relationship between both dataset, taking the spatial discrepancy into account. The results showed that the

correlation between the resampled canopy N and MTCI were significant regardless of the resampled pixel size. Moreover, an analysis investigated the influence of the spatial resolution on the remote sensing of canopy nitrogen. They could show that, even though the percentage of explained variance was reduced by going from high spatial resolution product to a low spatial resolution one (500 m), it was still possible to observe significant relationship between coarse spatial resolution remote sensing data and ground measurements (Lepine et al., 2016). This is mentioned in the discussion part of the manuscript in the section 4.5 (Line 362 – 365).

2) We addressed the temporal mismatch by averaging the MTCI product by month over the 10 years acquisition period, and selecting only the summer months, i.e. May-October, which corresponds to the growing season. By doing this, we decrease the influence of annual anomaly on the results. Moreover, the different selection criteria applied on the dataset, ensured that the plots that had undergone a land cover change were removed from the analysis. The consequence of this is that among the 846 plots included in the analysis, 625 were measured between 2000 and 2001. This is presented in the table 1. Finally, as you suggested in a later comment, an analysis of the inter-annual variation of canopy N data will be included in the manuscript.

Year	1988	1989	1990	1991	1992	1993	1994	1995	2000	2001
Number of plot measured	8	47	46	35	44	29	9	3	304	321

Table 1. Number of plots included in the analysis by sampling year.

3) To scale from leaf to canopy N, we use the leaf N value averaged of three individuals trees as the plot canopy N value. This methodology, i.e. using leaf N concentration averaged over several individuals as the plot level value, is common (Schlerf et al., 2010). In our study 96% of the plots were monospecific and 4% of the plots contained only two species, therefore we did not weight the average by the species abundance (Smith and Martin, 2001;Townsend et al., 2003;McNeil et al., 2007).

The paragraph about the leaf sampling method has been changed to stress that most of the plots were monospecific (Line 155):

A proportion of 96% of the plots included in this analysis were monospecific. 4% of the plots had two codominant species. For these plots, two leaf samples were collected, one for each of the codominant species found on the plots.

In this work, allometric equations are used to relate the diameter of the branches to the leaves dry weight in order to estimate canopy N content. It would be interesting to discuss the accuracy of this method compared to others proposed in the literature to estimate canopy foliar mass per species at the stand level.

Thank you for your comment. When analyzing this further, we found that the information provided in the original version of the manuscript about biomass calculation was incorrect. The foliar biomass data were calculated using allometric equations based on the diameter at breast height (DBH). The DBH was measured for all the trees present on the plot. This information is provided in two articles that also include data from the Catalonian National Forest Inventory (Vilà et al., 2003;Sardans and Peñuelas, 2015).

The paragraph in the canopy N data section 2.2.1 was changed accordingly (Line 148):

Along with the canopy N[%] data, we used foliar biomass data (g m-2) acquired during the same forest inventory (n = 2286). The foliar biomass data were obtained for each plot from allometric *equations relating the diameter at breast height to the leave dry weight. These allometric equations were species specific (Sardans et al. (2015), Vila et al. (2003), Table in supplementary information).*

It would be also interesting to know what is the inter-annual variation of N (ground measurements) in the study region in order to evaluate how this can affect to the discrepancy between timing of ground and satellite data.

We agree with you, the inter-annual variation of the ground measurements of canopy N is indeed essential due to the temporal discrepancy between our two datasets. As we have a large datasets covering the complete sampling period, studying the inter-annual evolution of the canopy N ground measurements would be possible. We will include this analysis in the revised manuscript.

Another important issue in this work is the lack of assessment of robustness of empirical models applied using either independent data or statistical techniques (bootstrap). This may be critical when the relationships found could depend on the covariance with other variables as is typically the case in the canopy N estimation from remote sensing.

Thank you, we agree with your comment. In order to assess the robustness of the relationships between MTCI and canopy N, a leave-one-out cross validation could be calculated for each of the relationships presented in the analysis. This would yield a Root Mean Square Error value that would give information about the prediction error of these relationships. This additional analysis will be included in the revised manuscript.

Finally, I also miss in the discussion how the authors consider the results could be potentially useful for monitoring canopy N at regional scale considering the strength of the relationships found and the estimation errors (not analyzed in the paper).

Thank you for your comment. The goal of this case-study analysis was to explore the feasibility of canopy N detection at regional scale using MTCI. Although the relationships are modest, our study contributes to the ongoing discussion about how to map canopy N over larger area, which could also lead to canopy N monitoring possibilities. This will be explained in the discussion part of the manuscript. We will also calculate the prediction intervals of canopy N data.

Specific comments addressing particular scientific/technical/formal issues follow:

Page 5 line 139. Complementary o alternative reference on methodology applied?

The explanation on the allometric relationship has been changed (Line 137):

Along with the canopy N[%] data, we used foliar biomass data (g m-2) acquired during the same forest inventory (n = 2286). The foliar biomass data were obtained for each plot from allometric equations relating the diameter at breast height to the leave dry weight. These allometric equations were species specific (Sardans et al. (2015), Vila et al. (2003), Table in supplementary information).

Page 5 line 143. Correct : : :.foliar biomass (N g per square meter: : :.

This has been changed in the text:
foliar biomass (dry matter g per square meter of ground area, g m^{-2}*)*

Page 5 line 153. Reword to clarify content and avoid repetitions

The sentence was clarified in the text:

A proportion of 96% of the plots included in this analysis were monospecific and had a single dominant tree species. There were 30 plots with two codominant species. For these plots, two leaf samples were collected, one for each of the codominant species found on the plots.

Page 6 line 180. Why the MERIS 300m full resolution product was not used instead?

Thank you for your question. We indeed first looked at using the MERIS 300 m full resolution reflectance images. These images were not used for our analysis for several reasons. The 300 m full resolution reflectance images available from the ESA are not corrected for cloud cover and atmospheric influences. Moreover, there is no temporally averaged product available at full resolution. This means that one image of the 300 m full resolution reflectance data is available every three to four days from 2002 until 2012. Each of the images included in this analysis would thus need to be atmospherically corrected (365/4 *10 ~ 912 images). This would have been very time intensive.

In this context, the MTCI 1 km level 3 product presented several advantages. It is a readily usable product that has been corrected for atmospheric influences and cloud cover and was monthly averaged. The availability of the MTCI monthly product made it possible for us to relate the ground canopy N measurements to 10 years monthly averaged without involving time consuming images processing. We believe that this way we could decrease part of the uncertainty of relating ground measurement to any daily remotely sensed reflectance value measured several years later. Finally, MTCI product is available for the extent of the Catalonia region in one single image, while the MERIS full resolution product can sometimes only partly cover the region and therefore each image would have had to be selected individually.

This will be more clearly explained in the Material and Method part, section 2.2.2 “MTCI product” of the revised manuscript (Line 159).

Page 7 lines 197-199. What about other land cover changes as those caused by forest fires (quite frequent in the study region), where they investigated and filtered?

The land cover changes caused by forest fires were not investigated in a separate way. As Globcover 2009 the land cover map includes a sparse vegetation class, which we believe is how the vegetation appears after a forest fire, the change due to forest fire should be accounted for when excluding sparse vegetation class from the analysis.

Page 7 sections 2.3.2 and 2.3.3. Would be interesting to know the number of plots per pixel (average, min and max) at the different spatial resolutions.

Thank you, we agree. The number of plots per resampled pixel size are shown in the table 2. This table will be added to the manuscript in the Result section 3.2 “Relationship between MTCI and canopy N data at lower spatial resolution”.

Table 2. Mean, minimum, maximum and standard deviation of the number of plots per pixel by the pixel spatial resolution (km).

Pixel spatial resolution (km)	average number of plots/pixel	minimum number of plots/pixel	maximum number of plots/pixel	standard deviation of the number of plots/pixel
5	1.5	1	6	0.8
10	2.3	1	11	1.5
15	3.2	1	15	2.6
20	4.5	1	22	4

Page 8 line 238. Foliar biomass is used in the calculation of canopy N content so the correlation is obviously strongest

Thank you, we agree with your comment. This was not intended to be understood as a new finding but we rather wished to be fully explicit about the correlation between the variables. The original sentence was replaced by (Line 238):
The correlation between each pair of variables was significant and the correlation between canopy $N_{[area]}$ *and foliar biomass was strongest (r = 0.88). This result was expected as the foliar biomass was included in the* $N_{[area]}$ *calculation.*

Page 9 line 254. Higher instead of lower
This has been changed.

Page 9 line 269. R2 for Quercus ilex?
The r2 value for *Quercus ilex* plots has been added in the text:

The relationship between MTCI and canopy N[area] was also investigated for 10 individual species and one of them showed significant relationships: Quercus ilex (r2 = 0.10, n = 160).

Page 9 section 4.1. Could the authors elaborate here on how this could affect to the regional estimation of canopy N using new generation Sentinel-2 and 3 with improved spatial resolutions?

Due to the higher spatial resolution of the MSI sensor onboard Sentinel 2 and the bands well positioned in the red edge region, remote sensing of canopy N at regional scale might be promising. However, a pre-processed product similar to the MTCI time series should first be made available to reproduce the methodology applied in this study. This has been addressed in the discussion section 4.5 "Perspective for larger scale applications" (Line 353):

In this context, the new sensors OLCI, onboard Sentinel 3 satellite, and especially MSI, onboard Sentinel 2 satellite, might also be promising due to their higher spatial resolution, from 10 to 60 m for Sentinel 2. They have bands well positioned to compute the MTCI vegetation index. Although the OLCI Terrestrial Chlorophyll Index (OTCI), the successor of the MTCI for the OLCI sensor, is already included in the OLCI level 2b reflectance image, no level 3 product similar to the MTCI time series used in this analysis, i.e. mosaicked over larger areas and temporally averaged, is available yet.

Page 11 line 315. Any hypothesis on the stronger relationship found for DBF plots? Further investigation on the proportion of the variance explained by other potential confounding factors would be desirable (same in lines 329 and 341)

Thank you for your comment. We will address the effects of the potential confounder on the relationship, among which biomass and canopy structure are related to the different PFTs, in the discussion part of the revised manuscript.

Page 11 lines 332-335. This has been already stated in the results sections. This apply for other paragraphs in this section, authors should avoid to repeat the results and focus on the discussion.

Thank you, we agree that repeating this information several times might be unnecessary. In this instance, we wanted to remind the reader what we are going to address in the next paragraph.

Page 12 lines 152-153. I would recommend to include the analysis in this paper using information acquired in the forest inventory used for the study.

Thank you for your comment. We agree that using additional data besides canopy N and foliar biomass would make the analysis stronger. However, only biomass and foliar concentration was measured during the forest inventory. Additional physiological data related to the forest plots is thus not available.

Page 20 FIGURE 1. Please clarify if the plots represented in the map are all the forest inventory plots (2300?) or 1075 (after temporal and spatial filtering) or 846/841 finally used in the analysis. I would recommend including only the plots used in the analysis.

Thank you, the number of plots represented in the figure (n = 846) has been added to the figure caption (Line 577). The number "1075" plots was mistake from a former version of the manuscript and has been changed where it appeared in the text.

Figure 1. Map showing the forest plots (n = 846) location in the region of Catalonia, north eastern Spain. DBF = Deciduous Broadleaf Forest, EBF = Evergreen Broadleaf Forest, ENF = Evergreen Needleleaf Forest, mixed = mixed forest.

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