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 #2
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We would like to thank the reviewer for reviewing our manuscript.

General comments: The paper aims to investigate the potential of using MTCI to map regional variations in canopy nitrogen (N). The study uses field measurements of canopy N for a large number of forest plots situated across Catalonia to derive empirical relationships between N and MTCI data across a range of spatial resolutions (1 - 20 km). The study also aims to identify the influence of plant functional type on the observed relationships. Whilst the premise of the work may be interesting, there are a number of questions and comments, some of which are fairly fundamental, which I feel need addressing before this manuscript can be considered for publication. The comments are provided in the hope that they may help improve the manuscript and its subsequent impact.

Specific comments: I am not entirely convinced of the justification for reducing the spatial resolution of the MTCI data. Why degrade the 1 km product? The MERIS sensor on board ENVISAT is no longer operational (which the author’s should note). The authors do note that a variation of the MTCI can be calculated from Sentinel-2 but this is a sensor with a higher spatial resolution then MERIS so what is the justification for making the data worse? Especially since the forest plots were substantially smaller than the original 1 km pixel size in the first instance. Averaging 6 m plots over a 1 km grid would “reduce small-scale variations (line 279)” so why 5, 10, 15 and 20 km also? Without this information the paper appears to be more of an academic exercise as opposed to addressing a tangible issue.

Thank you for your comment. This issue is indeed important as it addresses the spatial discrepancy between the two datasets, i.e. the forest plots used for the ground measurements (6 m) and the MTCI pixel size (1 km). Studying the relationship between canopy N and MTCI at a lower, degraded spatial resolution was done to overcome this spatial discrepancy and to study the relationships between our variables independently of the initial spatial discrepancy. This step also allowed us to study the influence of the spatial resolution of the MTCI pixel. The results showed that the relationships between the variable were not strongly affected by the resampling factor.

Moreover, we are afraid that there might have been some confusion. In section 4.1, we say that averaging 6 m plots over a lower spatial resolution, i.e. 5, 10, 15 and 20 km (and not 1 km), would reduce small scale variations. To make this more clear, we added the resampled pixel size in the text in section 4.1 (Line 278 - 282) as well as in the objective in the Introduction and Material and Methods sections were we felt it was lacking.

Finally, we agree with you that the fact that the MERIS sensor came to an end in 2012 is an essential information linked to our analysis. This was also noted in the original version of the manuscript (Line 166):
While the ESA ENVISAT satellite mission producing MERIS data came to an end in 2012

One of the main justifications for the study is that “limited research has been conducted to sense canopy N in Mediterranean ecosystems and even more so in Mediterranean forests”, yet there is no discussion of the importance of these ecosystems, or their N content. More information should be included to justify the significance of this sentence.

Thank you for your comment. Remote sensing of canopy N has not been done a lot in Mediterranean forest. We will include justification about the spatial and ecological importance, especially regarding species diversity (Vilà-Cabrera et al., 2018), of Mediterranean forests in the introduction part of the manuscript. We will also mention that there is a lack of studies and supporting data for Mediterranean ecosystems in global vegetation models studies (Line 40 – 41).

More information is required on how the forest plot data are deemed suitable for comparison with the MTCI data. There are several questions here:

1. Is the year of data collection an issue for the correlation? Perhaps colouring the points in figure 4 based on year of in situ collection may be useful e.g. were there any climatically anomalous years that could have influenced the MTCI relationships?

Thank you for your suggestion. In the figure 4, the plot ground measurements were averaged by pixel (20 km) and sampling month (over 10 years). This means that on the same pixel, the plots were measured during the same month and located at maximum 20 km from each other. However, these plots might have been measured during different years. The Material and Methods section 2.3.2 " Relationship between MTCI and canopy N data at lower spatial resolution" (Line 200) has been edited to make it more clear.
Colouring the points based on the sampling year might be an option, however, many of these points are likely to be the results of the average over several years. In table 1, we present the numbers of plots by sampling year. In the revised manuscript, we will also present the average number of year per pixel size.

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

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

2. How well do the 6m forest data plots represent the 1, 5, 15 and 20 km grid scales? There isn't any information as to how many points were included in each grid square when the data were resampled at each resolution. What was the distribution of values (mean, SD)?

Thank you for your comment. This is indeed important if we wish to evaluate the effectiveness of the resampling method to overcome the initial difference in support size. The table 2 shows the number of plots for each resampled pixel size. This table will also be included in the revised manuscript.

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

3. Can homogenous species plots be observed from satellite imagery at 5 – 20 km resolution? Surely the plots are going to be mixed species at this scale?

Thank you for your comment. Indeed, the plots are likely to be mixed species and mixed PFT too. This is the reason why the analysis by species and PFT was not carried out at this step of the analysis. Similar to the two previous question, we will present a table showing the average number of PFT and species per resampled pixel size in the revised manuscript.

The results presented, whilst statistically significant have quite low r2 values, which indicates that the precision with which N can be predicted will be low, even though there is a statistically significant relationship between the two variables. The authors do not comment on this but I think they should as this has practical implications for their suggested approach. It would be useful for the authors to suggest possible reasons why the reported statistically significant regressions are only explain 20 - 30% of the variation at best.

Thank you for your comment. The obtained r2 are indeed low, between 0.10 and 0.40. We would like to stress that other studies report similar or sometimes, lower r2, for analyses conducted at higher spatial resolution and in more controlled conditions (Cho et al., 2013;Wang et al., 2016). The obtained results were compared with existing literature in the section 4.2.1 "Canopy N concentration detection". This section was modified to stress the differences in spatial resolution (Line 288 - 296):

The performance of the MTCI vegetation index to detect canopy N[%] in Mediterranean vegetation was similar to the results obtained from previous studies using spaceborne MTCI at higher spatial resolution. For example, using MTCI computed from the spaceborne RapidEye sensor at 5 m spatial resolution, it was possible to detect canopy N[%] in grassland savannah and sub-tropical forest with similar coefficients of determination, r2 = 0.35 and r2 = 0.52, respectively (Ramoelo et al., 2012;Cho et al., 2013). However, while there is a consensus regarding MTCI ability for in situ leaf or canopy N[%] detection in a variety of crops using handheld spectrometers (Tian et al., 2011;Li et al., 2014), there is no general agreement about MTCI ability for canopy N[%] detection across vegetation and sensor types at larger scales. For example, MTCI computed from airborne data at 3 m spatial resolution could not be related to canopy N[%] from a mixed temperate forest (Wang et al., 2016). In this context our finding brings new insight into MTCI N[%] sensing capabilities at a much coarser spatial resolution (1 km) compared to what has been done before.

Moreover, we will address the potential confounding variables of the relationship between MTCI and canopy N in the discussion part of the revised manuscript. These confounding variables include biomass, canopy structure, LAI as well as climatic and geomorphological variables (Sardans et al., 2011;Sardans et al., 2016).

The goal of this case-study analysis was to explore the feasibility of canopy N detection at regional scale using MTCI. Although the statistical relationship are modest, the results provide spatio-temporal indicators of canopy N and we think that this analysis brings a valuable information in the ongoing discussion about the feasibility of sensing canopy N over larger spatial extent.

The authors indicate that these r2 values are somewhat lower than MODIS so why not just use MODIS?
Thank you for your question. We did not use MODIS because our goal was to test the relationship for the MTCI vegetation index. Vegetation indices products available for MODIS are NDVI and EVI, which have showed lower correlation with canopy N compared to MTCI due to saturation problem at high N concentration (Schlemmer et al., 2013;Pacheco-Labrador et al., 2014).
Moreover, the study we referred to in the discussion (Line 363 - 365), did in indeed get higher r2 using MODIS images. Their methodology was different as there was no temporal

discrepancy between their ground measurements and the satellite images acquisition. They worked with 7 x 7km MODIS tiles, while the MERIS MTCI level 3 product is available from the ESA for the extend of the whole region (and actually even Europe) in one single image.

Technical corrections:
The first sentence of the abstract is quite long. Consider fragmenting and re-wording to improve impact.

Thank you, the sentence has been changed (Line 10):
Canopy nitrogen (N) concentration and content are linked to several vegetation processes at leaf and canopy levels. Therefore, canopy N concentration is a state variable in global vegetation models with coupled carbon (C) and N cycles.

Line 11 and throughout – Data “is” should be changed to data “are” since data are Plural
This has been changed.

Line 13 etc. – The abstract should include some justification as to why the work is important. This could be more clearly explained in the abstract as opposed to simply saying x did this and we are doing that. The key question is why?
This will be added

Line 31: Delete “,” after processes This has been changed.
Line 35: Insert “,” after (N g m-2) This has been changed.
Line 48: Delete “Currently” This was changed. This has been changed.
Line 49: Insert “,” either side of from and sensors This has been changed.
Line 48 – 52: This is a very long sentence. Consider fragmenting.
This has been changed.

Line 53: No need for a new paragraph. This has been changed.

Line 68: “were aimed” is an odd choice of words. Consider re-wording
This has been changed.
most studies were carried out in agricultural crops using MTCI values computed from in situ hyperspectral reflectance data
Line74: Do the authors mean “a few studies” or “few studies”? It’s not clear as no references are referred to.
We mean here “few studies”. A reference has been added.

Line 83: “stated that the NIR – canopy N relationship was not necessarily spurious as plant traits have been known to covary along the leaf economic spectrum” This statement needs further explanation. What is meant by the leaf economic spectrum?
This will be explained in more details

Line 89: “MTCI time series could be applied to estimate canopy N at a larger scale” Be careful with the terms scale here. Do you mean over a larger spatial extent?
This has been changed.

Line 106: Suggests that there are 1075 forest plots but line 123 suggest that there are 2300 and in line 2017 there are 846 plots. Were some removed from the sample?
Thank you for noticing this mistake. On Line 106, 846 plots should have been written in place of 1075. This has been changed. The 2300 plots (Line 125) refers to the original number of plots included in the forest inventory before applying the selection criteria explained in the Material and Methods section (Line 216 – 218).

Line 110: What are the re-sampled resolutions and what is the justification for this?

Thank you for your comment. The resampled resolution are now clearly indicated in the text (Line 108):

Next, both data sets are resampled to the same, lower, spatial resolutions, i.e. 5 km, 10 k, 15 km and 20 km, in order to overcome the initial spatial discrepancy between MTCI spatial resolution (1 km) and the size of the forest plots (6 m).

Line 117: duplicate word "create": This has been changed.

Line 150: "Several (up to two times) " does not make sense. Several suggests three or more. Consider re-wording.

Thank you for your comment. This has been changed:

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.

Line 200: MTCI was not re-sampled as the product was already a 1 km product.

We agree with you that the initial spatial resolution of the MTCI product is 1 km. In the manuscript this is called the "higher spatial resolution". However, in our study we first analyze the relationship between MTCI and canopy N data after resampling both dataset to lower a spatial resolution (section 2.3.2 Relationship between MTCI and canopy N data at lower spatial resolution", Line 199). This was done to overcome the initial spatial discrepancy between the two datasets. To make this more clear, the resampled spatial resolution was added (line 201):

2.3.2 Relationship between MTCI and canopy N data at lower spatial resolution

In a first step, the relationships between MTCI and canopy N data values were investigated after resampling both datasets to the same, lower, spatial resolution. The resampled spatial resolutions were 5 km, 10 km, 15 km, and 20 km. This was done because of the initial difference in support size between MTCI spatial resolution and the forest plots size (i.e. 1 km and 6 m, respectively). This enabled us to investigate the relationships between MTCI and canopy N data independently of differences in initial support size.

Line 303-204: "This enabled us to investigate the relationships between MTCI and canopy N data independently of differences in initial support size." I don't entirely agree. Just because they now match on a spatial grid does not mean that the difference in sampling support size no longer matters. The crucial point is how well do the 6 m forest data represent the 1 km grid scale? Anything can be re-sampled. Whether it makes sense to do so is a different question.

Thank you for your comment. We chose to include the resampling analysis in our study due to the initial spatial discrepancy between the two datasets used, i.e. the ground measurements (6 m plots) and the MTCI pixel (1 km). By resampling both dataset to a lower and equal spatial resolution, we wanted to study the relationship between the two variables when the spatial discrepancy was accounted for. As you mention it, this process is dependent on spatial representativity of the plots found on the new resampled pixels. This has been addressed on the page 2 and 3 of this response. We looked at the number of plots per resampled pixel, the number of different species and PFT per resampled pixel as well as the number of different sampling years per resampled pixel. Moreover, Globcover 2009 landcover map was used to exclude from the resampling calculations the pixels that did not classify as natural vegetation. This was done to address the patchiness of the vegetation as explained on Line 204 – 206:

Tthe Globcover 2009 land cover map was used to exclude from the resampling computation the MTCI pixels located on land surface without natural vegetation cover. As for the forest plots, MTCI pixels *whose land cover class corresponded to rainfed cropland, mosaic between croplands and natural vegetation, sparse vegetation or artificial surfaces were excluded from the upscaling analysis*

Section 2.3.3. It seems a bit odd to investigate relationships at a lower resolution before you investigate it at the original spatial resolution.

Thank you for your comment. We choose to study the relationship at the lower spatial resolution before because we wanted to explore the relationship at higher spatial resolution in more details, i.e. by also PFT and species into account. At lower spatial resolution, this information about PFT and species is lost due to the resampling process.

Line 215: Refer to section numbers as opposed to "explained above"
The section number has been added.

Lines 219 and 220: delete the word "then" This has been changed.

Line 223: "The spatial analyses were done with the PCRaster software" It is not clear what spatial analyses were "done". Consider re-wording.

This has been added (Line 223):
Resampling both datasets as well as linking the plots to the MTCI pixels was done with the PCRaster software

Figure3: I am not sure what the purpose of this figure is since some of the variables being correlated are actually included in the calculation of others e.g. biomass and N concentration are both used to calculate N content – they are bound to be correlated. Hence line 238 is not really a finding.

This figure was included in the manuscript to summarize the information about the forest dataset. We also wished to be explicit about the correlation between the variables included in the analysis. The line 238 was not meant to be understood as a new finding but rather a statement about the correlation existing between the canopy N content and the biomass. This figure also show how the variables distribution are skewed.
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.

Line 282: I don't understand what this sentence means I'm afraid "This shows that, when the influence of the discrepancy between the original datasets was taken into account, MTCI and canopy N data were linked" what discrepancies were observed?

This sentence referred to the spatial discrepancy between the spatial resolution of the MTCI (1 km) and the forest plots (6m). The sentence has been rephrased.

Line 294 "there is no general agreement about MTCI ability for canopy N[%] detection across vegetation and sensor types" Can the authors bring any insights as to why this may be the case? What are the issues?

Thank you. The issue is that across different studies that investigate remote sensing of canopy N at larger scale, i.e. larger than with a handheld spectrometer, the prediction accuracy of the result is highly variable. When using a RapidEye at 5m resolution the prediction is similar to what we obtain. While the results obtained by Wang, 2016, even though at very high spatial resolution (3 m) were not significant. As we could think that the coarse spatial resolution might be a big obstacle to sense canopy N, our results showed that even though the spatial resolution was comparatively low (min 1km) we still get significant results. This thus adds to the discussion about canopy N remote sensing.

The paragraph has been edited to stress these distinctions (Line 291 – 303):
The overall relationship between MTCI and canopy N[%] at 1 km spatial resolution for all the forest plots (n = 846) was significant and the r2 value was equal to 0.32 (Fig. 5). This result showed that canopy N[%] could be related to MTCI in Mediterranean forests. The performance of the MTCI vegetation index to detect canopy N[%] in Mediterranean vegetation was similar to the results obtained from previous studies using spaceborne MTCI at higher spatial resolution. For example, using MTCI computed from the spaceborne RapidEye sensor at 5 m spatial resolution, it was possible to detect canopy N[%] in grassland savannah and sub-tropical forest with similar coefficients of determination, r2 = 0.35 and r2 = 0.52, respectively (Ramoelo et al., 2012;Cho et al., 2013). However, while there is a consensus regarding MTCI ability for in situ leaf or canopy N[%] detection in a variety of crops using handheld spectrometers (Tian et al., 2011;Li et al., 2014), there is no general agreement about MTCI ability for canopy N[%] detection across vegetation and sensor types at larger scales. For example, MTCI computed from airborne data at 3 m spatial resolution could not be related to canopy N[%] from a mixed temperate forest (Wang et al., 2016). In this context our finding brings new insight into MTCI N[%] sensing capabilities at a much coarser spatial resolution (1 km) compared to what has been done before.

Line 315-316 Consider re-wording. Also note that there were only 15 plots of Fagus sylvatica! Can you make such a conclusion based on relatively few samples?

Thank you. The sentence has been changed.
Moreover, when studied separately, the results observed for Fagus sylvatica plots (n = 15) were consistent with the stronger relationship observed for DBF plots.

Moreover, we agree that compared to the general size of our dataset, 15 Beech plots is relatively small subset but it provides a first indication. Moreover, many studies studying canopy N detection include very few samples in total. For example in a mixed temperate forest, Wang et al. (2016) included 26 plots (30 x 30 m) in total. In 2008, Huber et al. studied the remote sensing of canopy in a temperate forest using 28 plots (50 x 50 m) in total. In an arid shrubland, Mitchell et al. (2012) studied 35 plots (7 x 7m). These examples concern remote sensing of canopy N in general, i.e. they do not necessarily include MTCI, nor vegetation indices and use remote sensing sensors with high spatial resolution. Nonetheless, this can still give you an impression that 15 plots is not so uncommon.

Line 348 “Other authors, although agreeing that canopy structural properties needed to be accounted for, suggested that a direct biochemical link between canopy N and reflectance data was not necessary to detect canopy N with reflectance data (Ollinger et al., 2013;Townsend et al., 2013).” What did the authors suggest was necessary?

Thank you. Ollinger et al. (2008) used overall reflectance in the NIR and found a correlation with canopy N in boreal forest. Knyazikhin et al. (2013) argued that this relationship was spurious and resulted solely from differences in canopy structures linked to differences in PFT. Ollinger et al. (2013) and Townsend et al. (2013) argued that the observed relationship was not the result of a direct biochemical mechanism between nitrogen and incoming radiation but rather of an indirect link between nitrogen and plant structure, which would result from adaptive processes. We will modify the existing paragraph and add this information to the revised manuscript.

Section 4.4 doesn’t really come to any conclusions or suggest reasons for the PFT differences and so it is somewhat superfluous as it stands. Better to integrate this in a wider discussion or include some more detailed interpretation of the data.

Thank you for your suggestion. We will integrate the differences induced by the PFT in a wider discussion about the possible confounding factors that might influence the relationship between MTCI and canopy N. These confounding factors include biomass, canopy structure and climatic variables.

Lines 359-362. I do not follow this point here. What treatments were required and what "might reveal laborious" Consider re-wording.

Thank you. This sentence refers to the different treatments applied to images obtained with imaging spectroscopy at high spatial resolution with airborne or spaceborne sensors. These images need to be corrected for the influence of the atmosphere and clouds (atmospheric correction). Moreover depending on the initial sensor swath width as well as the size of the region to investigate, the images might need to be mosaicked into an image covering a larger area than the initial image acquired by the sensor. Depending on the time period for the ground measurements, the remote sensing images might also need to be temporally averaged. These treatments are similar to the one that would need to done to the MODIS images, as described on page 4 of this response.

This has been added to the manuscript (Line 359):

However, due to the different treatments required as well as the limited swath width associated with the high spatial resolution (from 3 m to 30 m for Hyspex airborne and Hyperion spaceborne sensors, respectively, Wang et al., 2016;Smith et al., 2003), applying imaging spectroscopy at a broader scale might reveal laborious. Depending on the sensors as well as on the extent of the study area, this might involve correcting the acquired images for atmospheric influences and cloud cover as well as combining several images into a larger scale image.

References:

Bartlett, M. K., Ollinger, S. V., Hollinger, D. Y., Wicklein, H. F., and Richardson, A. D.: Canopy-scale relationships between foliar nitrogen and albedo are not observed in leaf reflectance and transmittance within temperate deciduous tree species, Botany, 89, 491-497, 2011.

Cho, M. A., Ramoelo, A., Debba, P., Mutanga, O., Mathieu, R., van Deventer, H., and Ndlovu, N.: Assessing the effects of subtropical forest fragmentation on leaf nitrogen distribution using remote sensing data, Landscape Ecology, 28, 1479-1491, doi:10.1007/s10980-013-9908-7, 2013.

Huber, S., Kneubühler, M., Psomas, A., Itten, K., and Zimmermann, N. E.: Estimating foliar biochemistry from hyperspectral data in mixed forest canopy, Forest Ecology and Management, 256, 491-501, doi:10.1016/j.foreco.2008.05.011, 2008.

Knyazikhin, Y., Schull, M. A., Stenberg, P., Mõttus, M., Rautiainen, M., Yang, Y., Marshak, A., Latorre Carmona, P., Kaufmann, R. K., Lewis, P., Disney, M. I., Vanderbilt, V., Davis, A. B., Baret, F., Jacquemoud, S., Lyapustin, A., and Myneni, R. B.: Hyperspectral remote sensing of foliar nitrogen content, Proceedings of the National Academy of Sciences, 110, E185–E192, 10.1073/pnas.1210196109, 2013.

Mitchell, J. J., Glenn, N. F., Sankey, T. T., Derryberry, D. R., and Germino, M. J.: Remote sensing of sagebrush canopy nitrogen, Remote Sensing of Environment, 124, 217-223, 2012.

Ollinger, S. V., Richardson, A. D., Martin, M. E., Hollinger, D. Y., Frolking, S. E., Reich, P. B., Plourde, L. C., Katul, G. G., Munger, J. W., Oren, R., Smith, M. L., Paw U, K. T., Bolsta, P. V., Cook, B. D., Day, M. C., Martin, T. A., Monson, R. K., and Schmid, H. P.: Canopy nitrogen, carbon assimilation, and albedo in temperate and boreal forests: Functional relations and potential climate feedbacks, Proceedings of the National Academy of Sciences of the United States of America, 105, 19336-19341, doi:10.1073/pnas.0810021105., 2008.

Ollinger, S. V., Reich, P. B., Frolking, S., Lepine, L. C., Hollinger, D. Y., and Richardson, A. D.: Nitrogen cycling, forest canopy reflectance, and emergent properties of ecosystems, Proceedings of the National Academy of Sciences, 110, E2437, 10.1073/pnas.1304176110, 2013.

Pacheco-Labrador, J., González-Cascón, R., Pilar Martín, M., and Riaño, D.: Understanding the optical responses of leaf nitrogen in mediterranean holm oak (Quercus ilex) using field spectroscopy, International Journal of Applied Earth Observation and Geoinformation, 26, 105-118, doi:10.1016/j.jag.2013.05.013, 2014.

Sardans, J., Rivas-Ubach, A., and Peñuelas, J.: Factors affecting nutrient concentration and stoichiometry of forest trees in Catalonia (NE Spain), Forest Ecology and Management, 262, 2024-2034, doi:10.1016/j.foreco.2011.08.019, 2011.

Sardans, J., Alonso, R., Carnicer, J., Fernández-Martínez, M., Vivanco, M. G., and Peñuelas, J.: Factors influencing the foliar elemental composition and stoichiometry in forest trees in Spain, Perspectives in Plant Ecology, Evolution and Systematics, 18, 52-69, 10.1016/j.ppees.2016.01.001, 2016.

Schlemmer, M., Gitelson, A., Schepers, J., Ferguson, R., Peng, Y., Shanahan, J., and Rundquist, D.: Remote estimation of nitrogen and chlorophyll contents in maize at leaf and canopy levels, International Journal of Applied Earth Observation and Geoinformation, 25, 47-54, doi:10.1016/j.jag.2013.04.003, 2013.

Townsend, P. A., Serbin, S. P., Kruger, E. L., and Gamon, J. A.: Disentangling the contribution of biological and physical properties of leaves and canopies in imaging spectroscopy data, Proceedings of the National Academy of Sciences of the United States of America, 110, 10.1073/pnas.1300952110, 2013.

Vilà-Cabrera, A., Coll, L., Martínez-Vilalta, J., and Retana, J.: Forest management for adaptation to climate change in the Mediterranean basin: A synthesis of evidence, Forest Ecology and Management, 407, 16-22, 10.1016/j.foreco.2017.10.021, 2018.

Wang, Z., Wang, T., Darvishzadeh, R., Skidmore, A. K., Jones, S., Suarez, L., Woodgate, W., Heiden, U., Heurich, M., and Hearne, J.: Vegetation indices for mapping canopy foliar nitrogen in a mixed temperate forest, Remote Sensing, 8, doi:10.3390/rs8060491, 2016.