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Interactive comment on "Combining hyperspectral remote sensing and eddy covariance data streams for estimation of vegetation functional traits" *by* Javier Pacheco-Labrador et al.

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Authors' response: We would like to thank Referee #2 for the valuable comments. We will modify the manuscript to better explain many of the aspects that might have not been sufficiently clear. Some of the comments of Referee #2 suggest a change of the aim of our manuscript in order to exploit the existence of a fertilization experiment in the study area. However, the evaluation of the effects of fertilization is not the main target of this manuscript. Our work rather presents and evaluates the performance of a method capable of providing estimates of biophysical and functional parameters of vegetation combining hyperspectral and eddy covariance data. We will better stress the aim and scope and improve the discussion about the potential use of this approach at broader scales in the new version of the manuscript. We will also include in the discussion some considerations about the connection of our estimates with the fertilization, more specifically, by analyzing if the estimates are precise enough to discriminate these effects. More specific questions are addressed below.

Also, notice that in the new version we have introduced two changes:

1) A bug in the code that preserved carotenoids in the senescent leaves was been corrected. This has produced minimal differences in the results compared with the previous manuscript version.

2) A third step in the inversion has been implemented and tested to improve the characterization of the relationship between soil moisture and soil resistance to evaporation from the pore space. This had been only commented as a possibility in the discussion, but has been tested in the new version to confirm whether this could increase the certainty of this characterization without strongly modifying the estimates of other functional parameters.

Referee #2 comment: The work by Pacheco-Labrador et al. attempt to combine measured and emulated hyperspectral images with Eddy covariance (EC) flux measurements, to retrieve the tree-grass ecosystem physiological traits. In the work, the authors use a running fertilization experiment to build a model to predict the ecosystem physiological traits such as Vcmax and Ball-berry slope parameter (m). the authors do an inversion to the SCOPE model, and specifically the senSCOPE model that takes into consideration the senescence of leaves in the ecosystem. The measurements include three flux towers, one for each fertilization treatment. High spatial resolution airborne hyperspectral images have been taken during the experiment over the experiment. Also, isotopic samples were taken from the ecosystem as well. The emulated data used to introduce the potential of future satellite missions for ecosystem physiological traits retrieval. It is highly noticeable that the works contain a large amount of data from many years of measurements. Moreover, the combination of the fertilization treatments, in the heterogeneous ecosystem, using a wide range of measurements should bring to a robust understanding of the ecosystem physiological behavior. The use in the SCOPE model also allows to combine spectral and physical parameters measurements to retrieve ecosystem physiological parameters. However, reading through the manuscript leads to the filling that the current work was mainly the building of the model and less to achieve an understanding of the ecosystem relation between the measured spectral data and the physiological traits.

Authors' response: We agree with Referee #2 that the aim of our manuscript is not achieving an understanding of the ecosystem relation between the measured spectral data and the physiological traits. We aim to provide a method capable of filling a knowledge gap on the spatio-temporal distributions of key functional traits controlling carbon and water exchange, -such as Vcmax or the Ball-Berry slope m- by combining novel spaceborne hyperspectral imagery and eddy covariance fluxes. This gap implies for example the use of tabulated values of these parameters in terrestrial biosphere models which inflate uncertainties of predicted fluxes (see Rogers et al., 2017 or Walker et al., 2017); in this context, the use of novel remote sensing data, such as hyperspectral imagery, can contribute to better monitor and characterize vegetation function (Schimel et al., 2019)). This manuscript is a first step in a hypothesis that if successful, would allow estimating the temporal variability of these parameters in numerous ecosystem stations covering different biomes; and later on use this information to globally upscale this information (see Moreno et al., 2018 or Walker et al., 2017); which would allow filling a knowledge gap that limits the understanding and modeling of carbon and water fluxes.

Therefore, our manuscript focuses on presenting and testing the robustness of a method that could potentially be the basis of a global spatiotemporal characterization of key functional traits of vegetation. In this context, we do not aim to assess the effects of fertilization but rather the capability of capturing temporal dynamics. We use a study

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Discussion paper

site undergoing manipulation since it offers some advantages to test this methodology such as repeated eddy covariance fluxes in each campaign (three towers operate) and spatial variability in the biochemical, structure and function of vegetation that allow us to understand the robustness of the retrievals. The evaluation of vegetation responses to fertilization is a very interesting research question and several coauthors of this manuscript lead research in that direction, existing currently several works in preparation for submission, under review, or even accepted for publication in different journals. In general, these works require time series of different observations which are denser than the yearly airborne campaigns that we use in this manuscript.

We would also like to stress that in this manuscript we do not develop senSCOPE; this model is presented in another manuscript that for practical purposes has been openly archived (Pacheco-Labrador et al., 2020) and that is currently under review in another journal. The current manuscript presents an inversion approach that can be applied both to senSCOPE and SCOPE with the main aim of simultaneously estimating biophysical and functional traits. We test this approach in a complex ecosystem combining two vegetation layers with very different properties and phenology. Results suggest that the method is robust to several sources of uncertainty and that it would likely perform even better in other sites where models assumptions are better met.

We will clarify the aim and overarching goal of our manuscript in the text. Also, we will discuss which parameters might have been estimated with precision enough to reproduce responses expected from fertilization, in particular of Nitrogen.

References:

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Referee #2 comment: Moreover, it is a bit problematic to estimate the model performance in Infront of other estimated values (with their on uncertainties) and not with actual measured values. Estimation of Vcmax from leaves N content (which is also estimated part of the times, according to the authors) required a large number of assumptions and should be done carefully.

Authors' response: This comment is in part related with the fact that the assessments of the estimates and the databases involved have not been adequately described in the manuscript. In connection with comments made by Referee #1, we will improve the description of the different datasets generated and used in the manuscript as well as better justify how the evaluation of the different parameters is carried out. Part of these details will be presented in an additional figure as well as in a supplementary material that will improve the understanding of how and why this evaluation is done.

We acknowledge that the evaluation Cab and Vcmax is indirect, and mainly relies on nitrogen (N). We must stress that N was measured in the grassland and the trees in all the field campaigns where it is reported and was neither gap-filled nor estimated; this might not have been clear from the manuscript. This evaluation is not a direct comparison with observations of the assessed parameters as we acknowledge in the manuscript, but it is rather an alternative approach to overcome the lack of field observations. Since direct observations are not available for all the campaigns, we used additional estimates of these parameters as a reference to compare our estimates. However, we are aware and acknowledge that this is not a direct comparison. The lack of field observations representative of eddy covariance footprint-scale areas is usual problem in remote sensing, especially for functional traits controlling gas exchange rates such as Vcmax and m. Measurements of these parameters are strongly resource limited and strongly subject of scaling uncertainties when the study features numerous species. In this context, one of the contributions of the manuscript is proposing the use pattern-oriented evaluation approach to assess the estimates of functional traits that might not be frequently available the field.

One of the challenges that this and many other research works face is the evaluation of remote sensing based estimates. Mediterranean tree-grass (and other) ecosystems feature high species richness and spatial variability in the grassland, and a heterogeneity imposed by the coexistence of scattered tress and the grassland itself. This spatial variability must be accounted for during the estimation of ecosystem-scale vegetation parameters; which means that measurements must be taken at different locations and vegetation types, and then integrated according to the representativeness of the different samples in the ecosystem. This requires a sampling large enough (e.g., number, distribution and size of samples) to provide robust values, representative of the ecosystem. This is possible for biophysical parameters estimated via destructive sampling of vegetation material or canopy-scale technics: leaf biochemical contents or leaf area index. These parameters can be determined from samples of vegetation where the representativeness and individual values of the parameters of each species do not need to be individually measured; which reduces uncertainties propagated in the up-scaling (e.g., sampling all the vegetation material inside quadrants of known area). Years of sampling experience have shown the researchers working in our study site, the sampling strategy required to properly characterize the different vegetation types, according to their spatial and temporal variability (e.g., see Mendiguren et al., 2015 or Melendo-Vega et al., 2017).

However, functional parameters such as Vcmax or the Ball-Berry model slope m cannot be determined from bulk samples of vegetation; but must be measured leaf by leaf using gas exchange chambers for long periods of time (e.g. 40 min). Considering that the objective of such measurements would be providing values of the functional parameters representative of the eddy covariance footprint, the high spatial variability and species richness (quite evenly distributed in the grassland) would make necessary a huge number of measurements which could not be acquired due to time and technical limitations. Also, since these measurements would be species-based, the up-scaling process would be prone to high uncertainty. This problem is not only related to the study site, but to extensive areas comprehending numerous species or to diverse and rich ecosystems. For these reasons, we propose alternative methods (pattern-oriented evaluation approach) to assess estimates of functional parameters of vegetation. This approach relies on the capability of the model to reproduce expected patterns, either from the literature or from observations, with no prior knowledge about them. In order to evaluate Vcmax we rely on its relationship with nitrogen (N) assuming that the larger the presence of N in the leaf, the larger is the chance that this is placed in the Rubisco enzyme, therefore enhancing Vcmax. The specific relationship between both variables is species-dependent and changes according to different plant strategies. However, the existence of a positive relationship between N and Vcmax is known and has been shown for different vegetation types in the literature (e.g., Quebbeman and Ramirez, 2016; Walker et al., 2014; Feng and Dietze, 2013 or Kattge et al., 2011). Therefore, we exploit this knowledge to assess whether our estimates are plausible and reproduce expected relationships with other parameters or they are just loose equifinality or ill-posed solutions of the inversion. We are aware that there might sources of uncertainty but the fact that Vcmax scales with N according to what expect from a large body of literature shows that the retrieval of Vcmax is realistic. In the case of the Ball-Berry model slope m, we use the 13C discrimination as discussed and suggested by Seibt et al., 2008. Under certain conditions 13C discrimination and water use efficiency are inversely related. We are also aware of the limitations of this approach (e.g. Seibt et al., 2008; Medlyn et al., 2017); which we discussed in the manuscript. We took measures to minimize the effect of these additional factors, for example, we evaluated also underlying water use efficiency to minimize the effect of VPD, and considered only estimates close to the peak of the season, since 13C discrimination represents an integrative process whereas the m and uWUE vary in time or are rather instantaneous.

Another vegetation parameter that had to be evaluated indirectly was chlorophyll content since no field measurements in the grassland were available for most of the field campaigns; for this reason, this parameter was also evaluated indirectly. We used the relationship between chlorophyll content (Cab) and nitrogen (N) of the data available in these and other unrelated campaigns (see Melendo-Vega et al., 2017) to estimate grass Cab when missing, and then we scaled using trees Cab estimated in the field with a SPAD meter. On the contrary, the measurement of Cab in trees leaves using a SPAD meter took place in all the campaigns. It relies on solid and extensive datasets as well as on laboratory analyses that coauthors of this manuscript specifically refined to improve the photometric determination of pigments in the Holm oak leaves (Gonzalez-Cascon et al., 2017). Since most of the field estimates rely on the grass Cab-N relationship, we did not compare estimated and field Cab directly, but we rather looked at their relationship with N at ecosystem scale. This will be also clarified in the text.

The evaluation of our estimates is as thorough as possible given the constraints imposed by the ecosystem under study and the availability of data. We have carried out an evaluation effort not typically addressed in this sort of analysis, in order to provide plausible estimates; however, this process requires relying on some assumptions;

which we acknowledge in the manuscript. Many of the works dealing with the inversion of SCOPE evaluate Vcmax against NDVI, or simply comparing predicted and observed fluxes. Our work proposes the use of new evaluation methods that could contribute to other studies in the future.

In order to make this rationale more clear, we have stressed the assumptions behind the evaluations we carried out, especially in the case of the functional parameters, and increased the discussion of the consequences of their violation. We have also stressed the relevance of indirect evaluations when direct one are not feasible; this is necessary since functional parameters are more and more often evaluated from remote sensing, but not direct assessment is always available at this scales.

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Referee #2 comment: To my opinion, this work has a high potential to bring to a better understanding of the ecosystem physiological response through hyperspectral and EC measurements, however, several changes are required: - All the graphs (except to figures 2&3) do not mention the fertilization treatments, maybe this addition can explain part of the variance in the graphs.

Authors' response: We think as the Referee #2 that the analysis of the response to the fertilization of the ecosystem is indeed an interesting point, which is the objective of the experimental effort. However, this is not the aim of this manuscript. We'd rather exploit the variability induced by fertilization to test the robustness of the retrieval method to different conditions. We have stressed this idea now in the methods′ section; however, we have also extended the discussion to explain which parameters were estimated precisely enough to discriminate the effects induced by fertilization.

Referee #2 comment: - It looks like the summer measurements are not responding to the model, maybe the authors should consider excluding these results from the model, or at least to model them separately.

Authors' response: We agree with the Referee #2 in the fact that larger uncertainties occur during the dry period. The reasons for this are analyzed in the discussion section. We think that, rather than excluding this period it is important to include it in order to understand the potential risks and problems related with the study of this and similar ecosystems during the dry season. Notice that the inversion of the model is independently carried out for each date and tower; thus the presence of these data does not compromise the retrievals in other campaigns/periods. During evaluation, these data will be kept together to represent the total performance of the method. But we will stress this aspect as suggested by Referee #2.

Referee #2 comment: - In general, the discussion is mainly explaining the technical reasons for the model behavior against the other parameters. Maybe connecting the model to the actual physiology measured in the field will lead to a better understanding of the model strengths and weaknesses.

Authors' response: In response to a previous Referee #2 comment, we explained that the overarching goal of this manuscript, which is contributing to fill the knowledge gap about spatiotemporal distributions of key functional vegetation traits controlling carbon and water exchange in terrestrial biosphere modeling. We also explained that the scope of this work limits to the proposition and evaluation of a methodology that, when applied in numerous eddy covariance stations might eventually allow global up-scaling of these traits' distributions. In order to improve the understanding of the relevance and the aim of this manuscript, we will extend the discussion section, especially the first part, to stress the potential of this method and the need to test it in more and different ecosystems. We will stress that we demonstrated that the method is applicable in 3 different eddy covariance systems and with multiple imagery. We therefore think the method can be generally used, and the fact that it has been tested in a challenging ecosystem suggests that it could better perform in other sites where model assumptions are better met. The next steps will be an application on multiple sites with multiple hyperspectral imageries as soon as they will be available from recent or forthcoming space mission such as EnMAP, PRISMA, SBG, and/or DESIS, among others.

Regarding the part of the discussion on the uncertainties, we will try to streamline this section to meet the comment of Referee #2, but we also think that an open discussion on the uncertainties is very useful for the community. Some of the uncertainties discussed are specific of the ecosystem under study but not exclusive and a can affect also grasslands, or other ecosystems structurally heterogeneous. For example, it is well known that unidimensional radiative transfer models do not accurately represent canopies with strong geometrical scattering components due to the presence of occluding volumes. It is also known that the absorption coefficients and the refractive index used by leaf radiative transfer models are effective averages determined from different species. Thus, the properties of some types of vegetation might not be not always accurately represented. Our manuscript does not cover a large and diverse range of ecosystems, but we deal with problems that, with some differences, can be found in other remote sensing studies and sites. We will reinforce this idea in the discussion, and we will reinforce the need of thorough evaluation of these estimates. In this context, we will also strength the connection of our results with the phenology or the physiology of the site in order to discuss the reliability of the estimates and limitations of the method. However, notice that this is not the aim of this manuscript, and more complete and dedicated research has been carried out in parallel works using additional datasets such as denser time series of other measurements. Moreover, a deeper analysis of the model senSCOPE and its connection with physiology both measured and also simulated by the original model SCOPE is presented in the senSCOPE manuscript (Pacheco-Labrador et al., 2020).

References:

Pacheco-Labrador, J., El-Madany, T.S., van der Tol, C., Martín, M.P., Gonzalez-Cascon, R., Perez-Priego, O., Guan, J., Moreno, G., Carrara, A., Reichstein, M., & Migliavacca, M. (2020). senSCOPE: Modeling radiative transfer and biochemical processes in mixed canopies combining green and senescent leaves with SCOPE. bioRxiv, 2020.2002.2005.935064

Short comments through the MS:

- Line 77: Reference is required.

Authors' response: A reference will be added

- Line 79-80: This is a very simplified assumption. many works demonstrated that the atmospheric demand is highly relevant to the transpiration and stomatal response.

Authors' response: The statement will be rephrased to acknowledge also this fact.

- Line 86-87: Reference is required.

Authors' response: A reference will be added

- Line 112: Authors should consider referring to Fu et al. (2020), PCE "Estimating photosynthetic traits from reflectance spectra: A synthesis of spectral indices, numerical inversion, and partial least square regression". Authors' response: Thanks for the suggestion, we have considered the contents of this manuscript and we will include a comment to it in this part of the introduction.

- Line 215-216: WC is a tricky parameter; the leaf relative water content is a more reliable parameter in terms of plant water status.

Authors' response: This parameter is measured since it is one of the input parameters of the leaf radiative transfer model of senSCOPE. Its comparison with estimates is not presented in the manuscript but we confirmed that due to the lack of spectral reflectance data in the SWIR bands this parameter could not be constrained. This was commented in an early version of the manuscript but this comment was removed at some point during the preparation of the submitted document. We will bring it back to the results section as "The lack of information in the short wave infrared prevented adequate constrain of Cw (not shown)."

- Line 226: it is not clear how N content was measured please explain or add a reference.

Authors' response: We will improve the description of the field data used in this manuscript and on how these are integrated to ecosystem level. N determination is now explained in a dedicated supplementary material

- Line 226: which model was used? Reference.

Authors' response: This model was produced for time series of field data available in the study site. We will describe this analysis in a new supplementary material section.

- Line 230: Please note, if it is possible, if the estimation of Cab was done from estimated Nmass or only from measured values.

Authors' response: N was measured in all the campaigns where Cab of the grassland was not; therefore we used the observed relationship in the study site during additional campaigns (not concurrent to airborne overpasses) where grass N and Cab were simultaneously measured to gap-fill Cab in the campaigns where it was not available. This is now more extensively described in the dedicated supplementary material.

- Fig. 4: Fig. 4 please fit the letters in the legend to the figure.

Authors' response: The references to the subplots in the caption will be corrected.

- Fig. 6: to see all the points on the graph and avoid overlap, the authors should make them a bit transparent.

Authors' response: We will add transparency to the points in the plots.

- Fig. 7 please add parameters to the fitted curve and RMSE value.

Authors' response: Curve and parameters will be added. Figure 7 assess the retrievals of the soil resistance to evaporation from the pore space (rss) against soil moisture content. We acknowledge that this parameter is also potentially loose in the inversion, since its effect on the model outputs can saturate above some threshold (for Pacheco-Labrador et al., 2019); and in fact, the relationships between rss and soil moisture content presented in Figure 7 are poorly fit due to the presence of extreme values. Aware of this fact, we have implemented and tested a third step in the inversion where the relationship presented in Figure 7 is used as a prior to repeat the inversion carried out in Step #2. This leads to a much closer fit of the relationship between rss and soil moisture and more importantly, has little effect on the retrieval of Vcmax and m. This process was suggested in the discussion of the manuscript, but not carried out. We will include these results in the new version of the manuscript to show that a more robust relationship can be obtained.

- Line 565: replace “response”.

Authors’ response: Thanks, “response” was duplicated and will be removed.

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