Interactive comment on “Long-term water stress and drought monitoring of Mediterranean oak savanna vegetation using thermal remote sensing” *by* María P. González-Dugo et al.

Anonymous Referee #1

Reviewer comments are typed in black colour, whereas the responses are typed in blue colour.

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General Comments The manuscript present am interesting study using a long-term dataset to characterize the impact of water stress on the dehesa region of Spain. Overall, study was well designed, the paper is well written, and the results and conclusions are fully supported. however there are a few aspects of the study that need some clarification. The concerns, along with handful of minor grammar and typographical errors, are noted below.

We thank the reviewer for the constructive comments. We have considered all of them, the suggested changes and clarifications are detailed here and have been introduced in the revised manuscript.

Specific Comments

1. Line 13: The sentence beginning "Drought is a ..." might be expressed more clearly as : "Drought is a devastating natural hazard that is difficult to define, detect and quantify."

Sentence changed (line 13).

2. Line 13: The sentence beginning "Global meteorological data ..." is oddly constructed. It might be more clearly expressed as" The increased availability of both meteorological and remotely sensed data provides an opportunity to develop new methods to identify drought conditions and characterize how it changes over space and time."

The sentence has been changed (line 13-15).

3. Line 26: The sentence beginning "During the drier ..." is unclear and needs revision.

The sentence has been changed to: “During the drier events, the changes in the grasslands and oak trees ground cover allowed a separate analysis of the strategies adopted by the two strata to cope with water stress”. (line 27).

4. Line 34: The sentence beginning "Drought is a ..." could be expressed more clearly if constructed as: "Drought, which is both a devastating natural hazard and globally widespread, has complex consequences across spatiotemporal scales and sectors."

The sentence has been changed to the proposed construction (line 36).

5. Line 43: Replace "slow-onset nature" with "slow onset".

Replaced (line 45)

6. Line 48: Indicators of what?

Indicators of drought, it is now clear in the manuscript (line 50)

7. Line 53: The sentence beginning "LST and VIs" reads oddly. The authors seem to be saying that by combining information about the surface temperature and vegetation, remote sensing-based models can provide accurate estimates of ET. But, rather than statin that explicitly, the coach it in terms of vegetation indices etc.

The sentence has been deleted and simplified to: 'SEBM have been used to provide ET estimations over agriculture ... and agroforestry systems. (line 55).

8. Line 115: This paragraph is a bit unclear. The authors state the parameterization of green vegetation fraction and height are unique for the dehesa. Are the authors back calculating the leaf area index (L) using equations 8 & 9? If so, why? Also, there is no discussion of canopy height and how it's calculation is modified to better represent the dehesa.

Yes, we obtained Fc using eq. 8 and L is derived from Fc using eq.9. To clarify the procedure, we have modified eq. 8 and 9 to provide a more direct computation of L.

The computation of the canopy height was described in the manuscript, but the paragraph was unclear, and it has been modified (lines 155-165). Considering that the tree stratum of the dehesa is quite homogeneous in composition, dominated by mature Quercus ilex sp., and that grassland canopy has a very high variability of low height herbaceous species, the ecosystem structure has been simplified to compute hc in the following way: A constant height of 8 m has been assigned to oak trees, which is multiplied by its ground coverage in each pixel. Oaks fc is computed annually using summer NDVI in eq. 8. During the summer the grasslands are dry, and the only photosynthetically active vegetation contributing to the NDVI signal are the oak trees. The grassland height is low (< 1 m), affecting the effective canopy height of each pixel less than the trees, and it is also difficult to computed based on monthly vegetation indices given the high species variability. For this reason, the grassland height has been discarded and only the contribution of trees was considered to compute hc. We are aware that this is a simplification of a complex system that will contribute to the error of modelled fluxes. However, it was an operative solution considering the scale of this study.

9. Line 172: It would be helpful if the authors included a histogram and an estimate of the distribution skewness for ET and relative ET. From the description given here it appears quite small.

In the Figure S1 (supplement), we present the histograms (one for each month) of both variables. For both variables most months presented an approximately symmetric distribution, with skewness between -0.5 and 0.5, three of them were moderately skewed and only one month (for ET) and two months (for ET/ETo) were slightly above one. We have elaborated this point in the manuscript (lines 236-242). However, given the limited number of available points, these graphs only provide preliminary information and more data is required to confirm this point. For this reason, we prefer to include these graphs as supplementary information and not as part of the paper.

10. Line 182: Replace "presented a general good agreement" with "generally showed good agreement".

Replaced (line 260).

11. Line 184: Why the greater discrepancy for the turbulent fluxes compared to the C2 non-turbulent fluxes? Is this linked to imperfect closure for the flux measurements? Errors in partitioning the available energy between H and LE?

The imperfect energy balance closure is certainly a reason, as well as the discrepancy in the footprints of the different sensors (radiometer, soil heat flux plates, and the instruments for measuring the turbulent fluxes) and that of SEBS estimates. However, the different complexity in the formulation and computation of the radiative and the turbulent fluxes (the net radiation equation is a kind of linear representation, while the equation to estimate the sensible heat flux is highly non-linear), and the factors that influence each component (Rn is influenced by LWD, SWD, albedo and LST; H is influenced by LST, Ta, wind speed, NDVI, fc and LAI) also influence the final error. A small bias in LST, Ta, and vegetation information can cause a high bias in H (and thereby LE, compute as a residual). The soil heat flux has usually a low RMSD, but generally this comes with a higher relative error, due to the reduced magnitude of this flux.

12. Line 206: The sentence beginning "Very low runoff ..." is redundant and could be omitted.

The sentence has been deleted (line 285).

13. Line 207: Why isn’t the relationship shown? Although it reasonable to suspect these two quantities would be correlated, a "close" relationship is a bit of a surprise. It would be useful to show this relational.

In the supplement (Figure S2.) is shown the relationship between annual run-off measured at the Sta.Clo catchment reservoir and the annual aridity index (Budyko, 1974) estimated for the same catchment on the left, and the same relationship with the run-off (Q) also normalized by precipitation on the right. The shape of these relationships showed how variations in climate, as represented by variations of P and ETo, impact runoff and could provide a mean to assess the effects of a changing climate on water availability in this watershed. The budyko model represented in (b) was derived using Zhang et al. (2008) eq.9 with an adjusted value for α parameter equal to 0.54. It shows a mean to estimate long term annual run-off values in this catchment. Although these are interesting relationships, useful to complement the drought assessment, it’s a little outside of the topic and might disrupt the flow of the results, so we prefer to present it as supplementary material.

14. Line 207: Numerous metrics and indices have proposed been proposed over time to quantify aridity. It would be helpful to add a sentence or two to describe this index.

We have included in the text the following definition: “Annual……. the annual aridity index (Budyko, 1974) estimated at Sta.Clo following Arora (2002), as the ratio between potential evaporation and annual precipitation.” (line 288-289).

15. Line 222: Do the difference in the anomalies suggest local drought conditions? For example, during 2008/2009 there is a strongly negative value at the ES-LMa site while the value is slightly positive at StaClo. Would this indicate a local drought in the area about ES-LMa?

This is a correct observation. The difference is caused by the big difference in precipitation, as indicated in Fig. 3, precipitation at Sta.Clo (683 mm/a) is about twice that at ES-LMa (338 mm/a).

16. Line 253: it worth point out that the peak in the autumn is much weaker than the one earlier in the year.

Yes, it has been pointed out in the revised manuscript (lines 334,335).

17. Line 299: The phrase "and the more ..." also refers to ES-LMa, which was already discussed.

It has been deleted (line 392)

18. Figure 5: The word "fraction" is misspelled.

Corrected

References:

Arora, V. K.: The use of the aridity index to assess climate change effect on annual runoff. J. Hidrol. 265:164-177. 2002.

Budyko, M.I.: Climate and life, Academic Press, Orlando, FL, 1974.

Zhang L., N. Potter, K. Hickel, Y. Zhang, Q. Shao: Water balance modeling over variable time scales based on the Budyko framework – Model development and testing, J. Hydrol., 360: 117-131. https://doi.org/10.1016/j.jhydrol.2008.07.021. 2008

Interactive comment on “Long-term water stress and drought monitoring of Mediterranean oak savanna vegetation using thermal remote sensing” *by* María P. González-Dugo et al.

Anonymous Referee #2

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Reviewer comments are typed in black colour, whereas the responses are typed in blue colour.

General Comment

This paper deals with the modeling of drought in a oak savanna in Spain, where trees and pasture coexists, using ET estimates from thermal remote sensing data. I found the paper generally well written and well organized. The goal is clear, and the results sufficiently elaborate. However, I have three main concerns regarding the adopted methodology:

We really appreciate the time dedicated by the reviewer to read this manuscript and all the suggestions and comments that have been provided. We have considered all the comments, and the suggested changes and clarifications have been introduced in the revised manuscript.

1) the SEBS model is well-known in the remote sensing community for “instantaneous” application at the satellite overpass time (eventually followed by upscaling procedures to daily/monthly scale). Here the model is used on monthly data, but the authors fail to clarify how the model was adapted for the change in time scale (more details in the specific comment P8, L4).

The methodological section did not provide sufficient detail on how the different time step data were aggregated to SEBS inputs for the calculation. We have added a new section (new 2.2) to the revised manuscript dealing with “Model parametrization and dataset preparation” to clarify this issue. The monthly ET calculation using SEBS was demonstrated by Chen et al. (2014). The structure of the model was not changed regardless of whether it was used for instantaneous, daily or monthly ET calculations. The difference in its implementation was only due to the input datasets. For monthly ET calculation, monthly mean LST, air temperature, wind speed, downward shortwave radiation, downward longwave radiation etc were used. The accuracy of monthly LST, a key variable in SEB models, was evaluated by Chen et al. 2017, supporting its applicability for climate studies and numerical model evaluation. All these points are now clearly explained in the new 2.2 section.

References:

Chen X, Z Su, Y Ma, J Cleverly, M Liddell. (2017) An accurate estimate of monthly mean land surface temperatures from MODIS clear-sky retrievals, , Journal of hydrometeorology 18 (10), 2827-2847

Chen X, Z Su, Y Ma, S Liu, Q Yu, Z Xu. (2014), Development of a 10-year (2001-2010) 0.1 data set of land-surface energy balance for mainland China. Atmos. Chem. Phys., 14, 13097–13117. 2014. www.atmos-chem-phys.net/14/13097/2014/

2) The authors decided to use anomalies of the ratio ET/ETo as drought indicator. However, they do not provided neither evidences that this index perform better than others (e.g. even the simple ET), nor justification on why this index was used for the ecosystem under analysis (is it better suited for oak savanna than others?). Indeed, part of the study shift the focus on fc, because ET is not able to separate the behavior of trees and pastures. This analysis, even if interesting, is out of place give the declared goal of the study.

The reasons for the use of evapotranspiration anomalies to assess agricultural drought and a remote sensing-based surface energy balance model to estimate ET are provided in the introduction. However, as the reviewer indicates, the selection of the ratio of actual to potential ET was not explained in the manuscript. The reason why ET is normalised by ET_o is to separate the ET signal component responding to soil moisture from variations due to the radiation load. Therefore, this reduces the variability in ET due to seasonal variations in available energy. Anderson et al., (2011) showed that anomalies in ET/ET_o were more strongly correlated with other drought indices (including the US Drought Monitor, PDSI, PDMI, PHDI, SPI) than were anomalies in ET for most US climatic divisions, showing strong agreements in the southwest of the country, with a similar climate to the study area. This explanation has been added to the revised paper (lines 222-226).

However, following the reviewer's recommendation, a comparison between both series of anomalies (including also anomalies of Fc) has been performed (see figures below, in the supplement and new Fig 8). The result showed that, for the conditions of the study, the anomalies of ET and ET/ET_o performed similarly to characterize drought periods, presenting a high correlation (R^2=0.76 at monthly scale and R^2=0.82 at seasonal scale). It suggests that ET anomalies could be an option to monitor drought in dehesa areas. Nevertheless, the computation of ET_o does not require additional variables than those already used by the energy balance models, with a quite straightforward computation. Once actual ET is estimated, the computation of ET/ET_o takes very little effort and adds some confidence to the focus on the soil moisture signal. The graph of comparison of monthly anomalies has been included as the new figure 8 in the paper and these results are now discussed in the text (lines 373-383), including some comments to the rest of figures, presented as separate supplementary information. The justification of the selection of the ratio ET/ET_o is also included in the revised manuscript.

The explanation for the use of fc and its connection to the goal of the paper is included in the following comment.

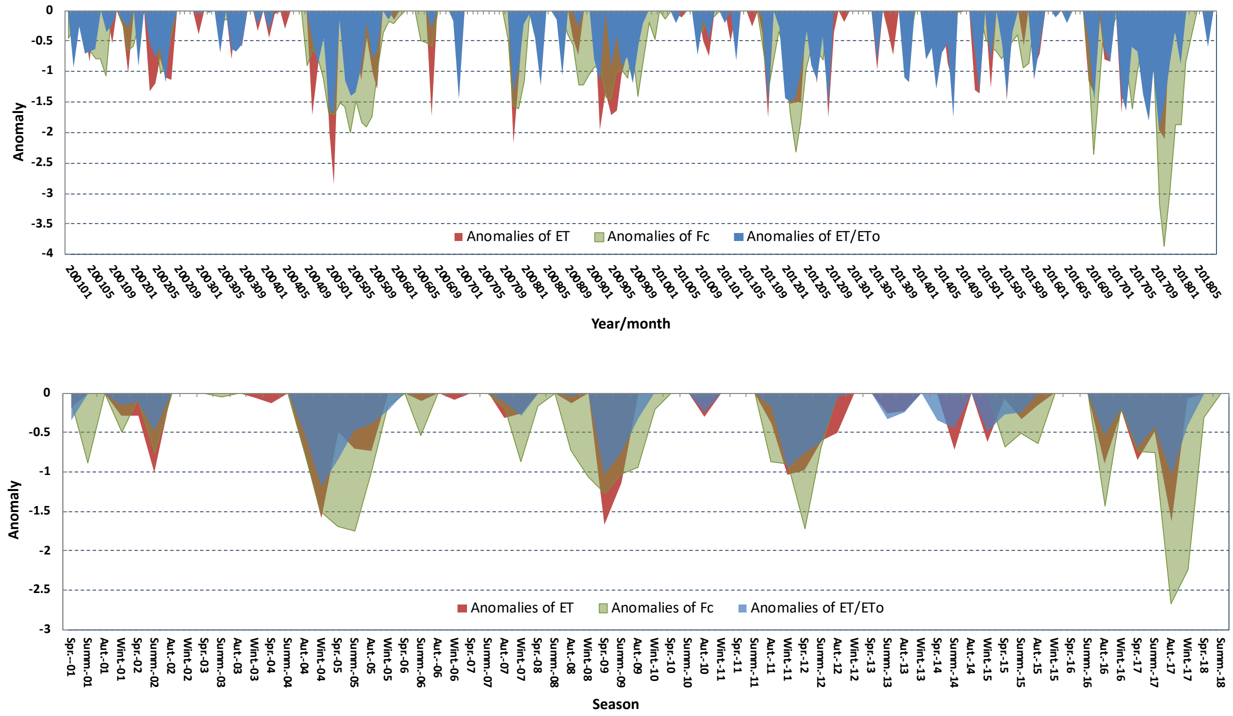
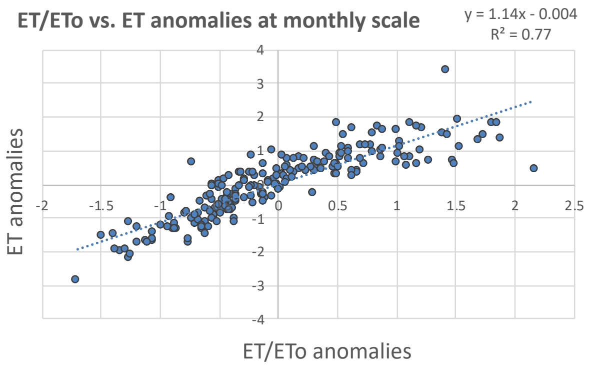
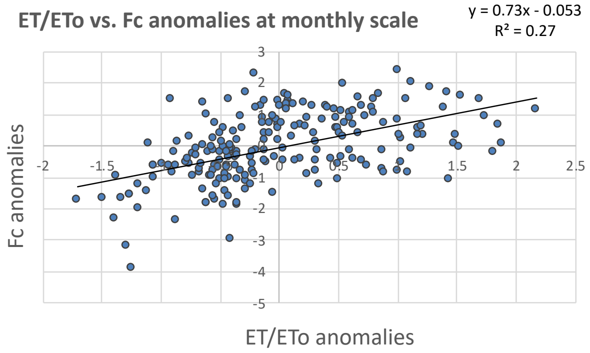
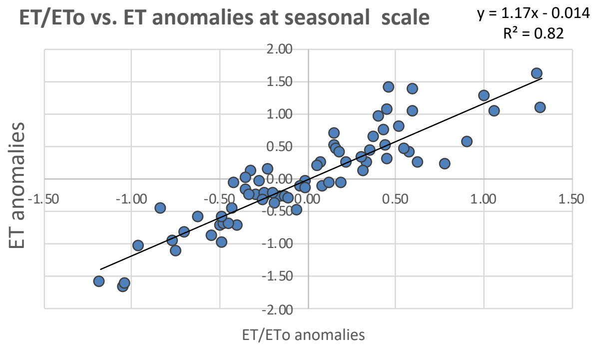


Figure comment 2. Comparison of ET/ETo, ET and *fc* anomalies at monthly and seasonal scale.







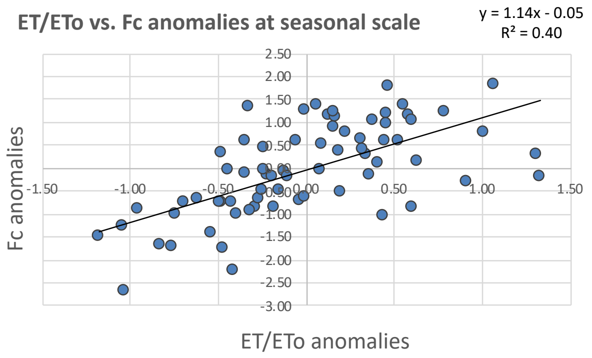


Figure S4. Relationships of ET/ET_o and ET anomalies at monthly and seasonal scales (left figures) and ET/ETo and ET anomalies at monthly and seasonal scales (right figures).

3) The authors used vegetation coverage and wheat productions as proxy of the drought impacts, without providing any justification for this choice. The first quantity is actually one of the input of SEBS, but is also weirdly used also for "validation", whereas the second is not necessarily related to drought impacts in a drought-resistant agropastoral system (see their words in P3, L6 of the manuscript).

The vegetation condition and the failure of crops are known consequences of a declining soil moisture and both have been used previously as indicators of drought (Liu and Kogan, 1996; FAO, 1983). Both variables, together with general numbers of hydroelectricity production, were the only available data that can provide a complementary view on drought impact in addition to evapotranspiration anomalies. As the reviewer points out, the green canopy cover is one of the inputs of SEBS and it is not used in the manuscript to validate the series of ET/ETo anomalies. However, the explicit analysis of its evolution sheds some light on the interpretation of these anomalies. In the case of wheat production, this rainfed winter cereal is the main agricultural use of dehesa areas. It is periodically sown in many pasture fields of this ecosystem. Its growth cycle is similar to that of the natural grasslands, with both of them escaping drought and coping with the long summer dry season by completing its life cycle before serious soil and plant water deficits develop. Given that no irrigation is provided, the impact of moisture deficits over its yield can be considered an indirect indicator of the impact of drought on all dehesa herbaceous vegetation.

An explanation justifying the use of both proxies has been be included in the methodological section of the manuscript (lines 248-254)

References:

Liu, W.T., Kogan, F.N., 1996. Monitoring regional drought using the vegetation condition index. Int. J. Remote Sens. 17, 2761–2782.

Food and Agriculture Organization, 1983. Guidelines: Land evaluation for Rainfed Agriculture. FAO Soils Bulletin 52, Rome.

In view of these considerations, I suggest the authors to revisit the manuscript to clarify these points before considering for publication. Some additional specific comments are also reported below, which I hope would be useful for improving the overall quality of the manuscript.

Specific comments

Title: I would replace the world "monitoring" with something else, since in my opinion monitoring implies something done in near-real time.

We have replaced the term *monitoring* by *assessment* in the title: "Long-term water stress and drought assessment of Mediterranean oak savanna vegetation using thermal remote sensing" and in some references along the text.

P2, L1: RMSD > xxx, and R2 < xxxx for all...

To provide a general idea of the global performance, we prefer to show average values rather than absolute ones for RMSD and R2. We have modified this sentence of the abstract to clarify it (line 20).

P2, L2-3: The details for each site are not needed in the abstract, especially after the previous sentence.

We are sorry but we are not sure to which "details for each site in the abstract" the reviewer's comment refers to. We don't provide details for each site separately there. There is a general comment "for both sites", which we consider relevant for the abstract.

P2, L8: "with the first one being. . .". I suggest to move this to a new sentence.

It has been changed (line 25).

P5, L4: Here I miss something that better links the previous description of the dehesa with the adopted modeling framework. In particular, why ET modeled by SEBS has been used? Is it a good option to capture the specificities of this environment (e.g. other options, such as dual source approaches, agri-forest modeling)?

We have not performed a comparison of different models' performance over this ecosystem. Several inter-comparison studies have evaluated different modelling schemes and no single one has been found consistently best across all biomes (Ershadi et al., 2013). The SEBS model has been selected here because it presents a good compromise between the detailed parameterization of the turbulent heat fluxes for different states of the land surface on the one hand, and the input requirements, kept to a feasible minimum and without requirements for local calibration, on the other (explanation added to the introduction, lines 58-60). Thus, it is a good candidate to produce global fluxes (Chen et al. 2019, Timmermans et al., 2013) and this work may contribute to improve the model parametrization for this type of ecosystems, usually poorly represented in land-atmospheric models. There was another practical reason, which is that the model had been previously applied with good results by Chen et al., (2014), at a similar spatiotemporal scale. Many operative solutions presented in that paper were also used here, simplifying its implementation.

References:

Chen X., Z. Su, Y. Ma: Remote sensing of global monthly evapotranspiration with an energy balance (EB) model. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W13, 2019 ISPRS Geospatial Week, Enschede, The Netherlands. https://doi.org/10.5194/isprs-archives-XLII-2-W13-1729-2019. 2019

Chen X, Z Su, Y Ma, S Liu, Q Yu, Z Xu. (2014), Development of a 10-year (2001-2010) 0.1 data set of land-surface energy balance for mainland China. Atmos. Chem. Phys., 14, 13097–13117. 2014. www.atmos-chem-phys.net/14/13097/2014/

Ershadi A., M.F. McCabe, J.P. Evans, N.W. Chaney, E.F. Wood: Multi-site evaluation of terrestrial evaporation models using FLUXNET data. Ag. Forest Meteorol. 187: 46–61 http://dx.doi.org/10.1016/j.agrformet.2013.11.008

Timmermans J., Z. Su, C. van der Tol, A. Verhoef, and W. Verhoef: Quantifying the uncertainty in estimates of surface–atmosphere fluxes through joint evaluation of the SEBS and SCOPE models. Hydrol. Earth Syst. Sci., 17, 1561–1573, 2013. doi:10.5194/hess-17-1561-2013 www.hydrol-earth-syst-sci.net/17/1561/2013/

P6, L3: I would suggest to write the eq. as LE = Rn - . . .. since you already introduced concept of LE as residual.

The equation has been rewritten.

P6, Eqs. (4) and (5). The second eq. is redundant.

Eq.5 has been removed.

P7, Rqs. (6) and (7). These two equations are confusing. In LEwet is computed via (6), then Hwet needs to be defined in another way, or vice versa. Please clarify.

Eq. (6) has been similarly removed and Eq. 16, of Su (2002) has been added for the calculation of H_wet (new eq.6).

Su Z.: The surface energy balance system (SEBS) for estimation of turbulent heat fluxes. Hydrol. Earth Sys. Sci., 6(1), 85– 99, 2002.

P7, L3. The way the limits are used needs a better clarification.

The explanation of the limits has been extended (lines 119-216) in the manuscript and it clearly refers now to Su (2002) for a full description on the use of the limits (lines 135).

P7, L4. if Hwet is derived from Eq. (7), LEwet needs to be defined by an eq. that is not (6) (e.g. Penman-Monteith as stated afterward).

A new equation to compute H_wet (new eq. 6) and the corresponding explanation has been added, LE_wet is derived from eq. 5.

P7, L5. ". . . a set of assumptions. . .". Please provide a brief description of these assumptions.

This explanation has been modified with the addition of a new equation and the assumptions applied to obtain it (lines 124-126).

P7, L7. The role of canopy height is not clear at this point for a reader that is not familiar with the model. Please briefly introduce where and how hc plays a role. Also, the authors introduced a "revised version of the model. . . new bare soil resistance" (P5, L18), but the role of this new parameterization is not clear since there are no mention of resistance in the model description.

The canopy height is needed for calculating the momentum roughness length and thus, important for the sensible heat calculation. This information has been added to the text (lines 155-165). Concerning the bare soil resistance, as the reviewer observed, it is not mentioned in this brief description of the model. To avoid confusion, we have deleted this comment and we refer the reader interested in a complete description of the model to previous papers (lines 103- 104).

P8, L4. The SEBS model has been designed for "instantaneous" application at the time of LST acquisition. As a consequence, more details needs to be provided on how the authors adapted the model to work on monthly LST. I think that the idea is to use monthly LST as a "artificial" instantaneous LST for a theoretical average day, but some questions that needs to be addressed are: - how did you ensure consistency between the mosaicked monthly LST and 6h ECMWF meteo forcing? - How 16 days NDVI was used jointly with monthly LST? - How daily upscale was performed? - How monthly upscale was performed?

This issue was mostly addressed in the first point of the general comments. It was clarified that no model upscale was performed. LST and all the meteo forcing used to run the SEBS model in this study were monthly mean values. Monthly mean meteo forcing were directly provided by ECMWF (available for download in its website). Monthly mean LST was processed following the work of Chen et al. (2017) referenced above. Monthly NDVI was derived from 16 days NDVI by selecting the maximum values in each month. All this information has been added to a new methodological section (2.2) dealing with dataset preparation.

P9, L1. Some details on the balance closure would be helpful. Was closure forced, and with which method? How were the data cumulated at monthly scale (I'm assuming some unavoidable missing data during the acquisition, any constrain on minimum data, etc.)?

The closure of the balance was forced using the residual method. For ES_LMa the processing of the data (gap filling, monthly aggregation) corresponded to the procedure standardized by Fluxnet (described here: https://fluxnet.org/data/fluxnet2015-dataset/data-processing/). In the case of Sta.Clo, the comparison period was selected attending to the quality of the data and some month were discarded due to missing information. A new paragraph with some details on data selection and processing has been added to the manuscript. (lines 199-203).

P10, L13. It would be interesting to have a couple of words on the reason behind the use of ET/ETo rather than ET itself for the computation of anomalies. In my experience, there are many cases where ET anomalies are a better proxy of drought that ET/ETo ones. Ideally, the authors should add a test showing that ET/ETo outperform ET alone (especially with the latter being a more conservative approach, which does not need any additional quantity).

We have included in the revised version of the manuscript an explanation for the reasons behind the use of ET/ETo rather than ET itself for the computation of anomalies. In addition, we have compared both anomalies at monthly and seasonal scales, part of this analysis will be presented in the manuscript with a new figure and the rest as supplementary information. Detailed information regarding this point has been previously described.

P10, L15. I have some issue with the use of fc as proxy of drought impacts, especially when fc is also one of the input of SEBS. If fc is a good proxy of drought impact, why we should use a complex model such as SEBS (which uses fc as input) to derive a quantity (ET) which performance is evaluated against fc. Why don't we use directly fc (or rather fc anomalies) at this point?

We have justified above the way of using fc in the paper. Regarding the evaluation of Fc anomalies, a new analysis has been performed to compare its performance to drought assessment with ET and

ET/ETo anomalies (see figures of the general comment 2). From these figures, both at monthly and seasonal scales, it can be derived that the drought events identified using the three variables would have been the same, but with different intensities and duration. The main differences can be found during the cold winter months when the vegetation is largely dormant. In these cases, the anomalies of Fc, similarly to the performance of other indices based on vegetation as the Vegetation Condition Index (VCI) (Heim, 2002) have a limited utility. The results are more comparable and could be more useful during the growing season. This discussion has been added to the text. However, the explicit analysis of fc evolution sheds some light on the interpretation of these anomalies. An explanation justifying the use of this proxy has been included in the methodological section of the manuscript (lines 248-254).

Heim, R. R., 2002: A Review of Twentieth-Century Drought Indices Used in the United States. *Bull. Amer. Meteor. Soc.*, **83**, 1149–1166, https://doi.org/10.1175/1520-0477-83.8.1149.

P10, L18. Similarly, I miss the connection between the impact of drought on the dehesa (a predominantly oak savanna) and wheat production. I know that having an independent estimate of drought impacts is tricky, but if the focus of the paper is specifically for the dehesa, you should justify better why wheat production is a good proxy of the drought impact on a likely drought-resistant, adapted oak savanna. The use of this quantity risks to lost the specificity of the work that you introduced earlier.

We have justified the use of wheat production as a component of dehesa and attending to its similar growth cycle to natural grasslands. The impact of moisture deficits over its yield can be considered an indirect indicator of the impact of drought on dehesa herbaceous vegetation. This point has been clarified in the methodology of the revised manuscript (lines 252-254).

P11, L12. It would be better to have the results disaggregated for seasons, in order to better highlight the impact of this seasonality in the error. This would help discussing the results, since drought may be mostly concentrate in some seasons. Also, since your goal is to use ET/ETo anomalies as proxy for drought, it would be much better to have in addition a validation of both ET/ETo values and z values against ground data. Even if the length of the time series is quite short, it is important to show that the model is able to capture the year-to-year fluctuations, since this is what you want to reproduce. Often, ET estimates are “well” modeled only because the area has a strong yearly cycle.

Of the different temporal scales to show the results, we have selected the most extreme available (year and month). The seasonal information can be derived from Figure 7 for ET, ETo, P and fc and the identified dry period. The validation of ET estimated, as shown in Figure 2, is performed on monthly data.

P12, L1. It is weird to me that you show the yearly-aggregated data before the monthly one. Apart form that, Figure 3 is a good example of my consideration on P10, L13. Just looking at the plot, it seems that ET capture the same events that ETo if Precipitation is used as reference. What is the added value of using ET/ETo rather than ET alone?

We chose to present the results from a coarser temporal scale to provide a more general vision of the evolution of drought years to more detailed monthly results in which we can discuss shorter term variations.

P12, l15 to P13, L5. This whole paragraph seems a little out of topic to me. I suggest to reword to clarify the role in explaining drought in the region, or remove it completely.

This first part of paragraph (in the original text, lines 207-212) is intended to describe the area of study in terms of aridity and provide some numbers corresponding to the experimental sites, to classify them in relation with other climate areas of the world. Information complementing this description has been included as supplementary material (Figure S2), and some clarifications have been added to the text (lines 287- 289). The second part (in the original text, lines 212-216) compares the two sites and discusses some aspects of Figure 3, as the relation between ET and ETo at annual scale, that we consider related to the topic of the paper.

P13, L13. Please define a mild drought. Also, it is not clear to me what is the role of this intercomparison between the modeled data over the two sites. Please clarify the aim of this comparison and justify the inclusion of a dedicated figure.

We define drought intensity in terms of maximum negative anomaly of relative ET values reached during the event (thus using the standard deviation as a measure of its departure from the mean). For the analysis of the events that occurred during the study period, the following thresholds were used: severe drought (anomalies <=-1.5); moderate drought (anomalies between -1 and -1.5) and mild drought (anomalies between -1 and 0). These classes are used for both annual and monthly time steps. This information has been included in the revised text (lines 243-247).

The intercomparison between sites complements the information provided on the experimental sites used to validate the model. In addition, we don't present a complete disaggregate analysis and most of the paper is focused on the whole dehesa region. This figure of the experimental sites points out that the general patterns are similar but there exist local differences and provides an estimate of the magnitude of these differences.

Fig. 5. Again, what is the added value of ET/ETo anomalies over ET alone (or, even worse, fc)? If anything, these figures are convincing me even more that a complex modeling framework is not needed, at least at annual scale. I'm sure that there is something more, but this is not discussed and justified by the accompanying text.

This issue was addressed above and also in the manuscript, including a new analysis and a new figure comparing the anomalies of ET/ETo, ET and fc at monthly scale. In the complementary information the analysis is extended to the seasonal scale.

Fig. 6. There is an odd strikingly resemblance between the spatial patterns in the years 2004/2005 and 2011/2012. Can you elaborate a little more on that?

Yes, both maps look quite similar, but they are different. An option for the analysis could be to produce a difference map to analyze similarities and differences. This will be considered in a future analysis at local scale.

P15, L2. Is this the average over the whole dehesa? A single point? Other? Please clarify. Also, in case of the average, it would be interesting to see if also the spatial variability (std.dev) shows interesting results.

Yes, it is the average. We will analyze the std.dev in later work.

P15, L12. What about the intra-annual fluctuactions? Are they similar to ET/ETo z values also at this temporal scale? Any temporal delay?

We don't fully understand this question, we presented the monthly data to analyze the intra-annual fluctuations. The comment has a different number of page/line than the manuscript we have. In most comments, we have identified the reference attending to the content but in this case it's not completely clear.

P15, L19. Similarly to comment P13, L13, duration and intensity of drought needs to be defined in the methodology section.

We define the duration of the drought as the successive number of months with negative anomalies and the intensity as the maximum anomaly in this continuous period. These variables have been defined in the methodology.

P16, L11 to P17, L9. These results are interesting but a little out of place in a paper on "drought monitoring using thermal remote sensing", as you stated in L10 (A more detailed analysis is required...). Above all, this analysis suggests, again, how the adopted modeling framework may not be ideal for the study of this specific biome. Please justify this analysis in the context of the main goal of the study (thermal remote sensing), and against the use of ET/ETo as drought proxy.

The focus of the paper is on the assessment of long-term water stress and drought in dehesa ecosystem, the means used is thermal remote sensing, and *fc* evolution is also used to interpret anomalies of relative ET. The modelling framework used here is not the only plausible approach to monitor drought in this biome. However, the results have shown that it is well fitted for this system.

Interactive comment on “Long-term water stress and drought monitoring of Mediterranean oak savanna vegetation using thermal remote sensing” *by* María P. González-Dugo et al.

Anonymous Referee #3

Received and published: 15 July 2020

Reviewer comments are typed in black colour, whereas the responses are typed in blue colour.

General comments:

The study by Gonzalez-Dugo et al. presents an interesting analysis of long-term ET and drought indicators over an Oak savanna region in Spain. The study implemented a surface energy balance model (i.e. SEBS) together with MODIS products and ERA meteorological data to obtain monthly and annual water stress indicators for a 17-year period. The manuscript demonstrated a sound remote sensing-based methodology and is valuable to better understand the long-term effects of droughts over an important and complex region such as the Spanish dehesa, which may be also relevant for other similar savanna-like ecosystems. The analysis of the monthly and annual time-series demonstrated an important dataset that helps to better characterize and understand drought events (and their effects) in these water-limited ecosystems. The results and conclusions were well described and articulated.

However, I have some comments related to certain details of the model set-up, which were missing or not clearly elaborated in the methodology section. Since the study presents a workflow to obtain long-term water stress indicators, more information on how the input datasets were pre-processed is needed (e.g. retrievals of inputs, resam- pling of datasets at different temporal and spatial resolution) so this workflow can be reproduced for other studies/applications. Additionally, it was not very clear how the authors tackled the issue of having different vegetation covers (i.e. trees and grasses) and if the model inputs/structure reflected this added uncertainty in these types of land-scapes. The retrieval of certain inputs, especially important ones like LAI and canopy height, should be more clearly described. In addition, the study should more clearly show the particularities of the dehesa system and how the methods presented here are more sound for monitoring dehesa (and similar) ecosystems compared to other ET products such as, for example, the MODIS ET product.

The study is concise and relatively well written. However, the authors should review certain sentences and try to write with more direct language in certain situations (see the specific comments below for examples).

Overall, I would recommend accepting this manuscript after revising and addressing the comments specified below.

We really appreciate the time dedicated by the reviewer to read this manuscript and all the suggestions and comments that have been provided. We have considered and answered below all the comments. The suggested changes and clarifications have been introduced in the revised manuscript.

Specific comments:

L44-45: Here, the authors briefly mention the complex canopy structure of the agro-system and how it causes an added difficulty to assess and monitor droughts. However, a few more details on the particularities of dehesa/savanna ecosystems is needed in the introduction and, more concretely, why these ecosystems demonstrate greater uncertainty when using modeling methods, such as surface energy balance models especially compared to landscapes with more homogeneous canopy covers and structures. This would further justify the study, which provides a methodology that monitors ET and drought for an ecosystem that tends to be poorly represented by land-atmospheric models, usually causing for greater uncertainties.

Similarly to other savanna ecosystems, the different components of dehesa structure: sparse tall vegetation, large areas of grasses, shrubs, and bare soil, contribute differently to the turbulent exchange and radiative transfer, hindering its modeling especially when compared with more homogeneous landscapes. In addition, these vegetation layers differ in phenology, physiology and function: while the trees are evergreen and have access to deep sources of water all year, the herbaceous layer only taps water from the first cm of soil and dries up during summer. The combined different functioning and characteristics of the system components affects the exchange of sensible and latent heat flux, resulting in a high spatial and temporal flux variability difficult to account for in model parametrization and algorithms. This structure appears to play an important role in savannas' resilience, making the system an efficient convector of sensible heat and keeping the canopy surface temperature inside the adequate range for survival (Baldocchi et al., 2004). A brief explanation of the influence of dehesa characteristics on energy flux modelling has been added to the introduction of the paper (lines 79-87).

References:

Baldocchi, Dennis D. and Xu, Liukang and Kiang, Nancy. (2004) How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland Agricultural and Forest Meteorology, 123: 13-39. doi: https://doi.org/10.1016/j.agrformet.2003.11.006

L74: Why was SEBS used compared to other models? A small justification is needed for the use of SEBS. What advantages does it present compared to other models? Why not other thermal-based SEB models such as e.g. METRIC, SEBAL, TSEB etc or optical-based PM/PT methods as used in the MODIS ET product. Or even the use of products from geostationary satellites such as LSA-SAF ET.

We have not performed a comparison of different models' performance over this ecosystem. Several inter-comparison studies have evaluated different modelling schemes and no single one has been found consistently best across all biomes (Ershadi et al., 2013). The SEBS model has been selected here because it presents a good compromise between the detailed parameterization of the turbulent heat fluxes for different states of the land surface on the one hand, and the input requirements, kept to a feasible minimum and without requirements for local calibration, on the other (this explanation has been included in the introduction of the revised paper, lines 58-60). Thus, it is a good candidate to produce global fluxes (Chen et al. 2019, Timmermans et al., 2013) and this work may contribute to improve the model parametrization for this type of ecosystems, usually poorly represented in land-atmospheric models as the reviewer mentioned in the previous point. There was another practical reason, in that the model had been previously applied, with good results by Chen et al., (2014), at a similar spatiotemporal scale that the one of interest for this application. Many operative solutions presented in that paper were used also here, simplifying the implementation of the model.

References:

Chen X., Z. Su, Y. Ma: Remote sensing of global monthly evapotranspiration with an energy balance (EB) model. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W13, 2019 ISPRS Geospatial Week, Enschede, The Netherlands. https://doi.org/10.5194/isprs-archives-XLII-2-W13-1729-2019. 2019

Chen X, Z Su, Y Ma, S Liu, Q Yu, Z Xu. (2014), Development of a 10-year (2001-2010) 0.1 data set of land-surface energy balance for mainland China. Atmos. Chem. Phys., 14, 13097–13117. 2014. www.atmos-chem-phys.net/14/13097/2014/

Ershadi A., M.F. McCabe, J.P. Evans, N.W. Chaney, E.F. Wood: Multi-site evaluation of terrestrial evaporation models using FLUXNET data. Ag. Forest Meteorol. 187: 46–61 http://dx.doi.org/10.1016/j.agrformet.2013.11.008

Timmermans J., Z. Su, C. van der Tol, A. Verhoef, and W. Verhoef: Quantifying the uncertainty in estimates of surface–atmosphere fluxes through joint evaluation of the SEBS and SCOPE models. Hydrol. Earth Syst. Sci., 17, 1561–1573, 2013. doi:10.5194/hess-17-1561-2013 www.hydrol-earth-syst-sci.net/17/1561/2013/

L116: It says ‘The green canopy cover and leaf area index (L) were calculated using the following equations (Choudhury et al., 1994)’ however equation 8 or 9 do not detail how leaf area index was computed (only fractional cover, fc)

Fc is calculated using eq.8 and L is derived from *fc* using eq. 9. However, to clarify the procedure we have modified eq. 8 and 9 (new eq. 7 and 8) to provide a more direct computation of both variables.

L125-129: It is not very clear how the canopy height was estimated. Is the canopy height assumed to be 8m, as such only accounting for tree and neglecting the grass/pasture or is it an integrated/effective value based on NDVI? If not ignoring the grass, how is the grass canopy height estimated? What is the relationship between NDVI and canopy height? I suggest to re-write this paragraph to makes this clearer and more specific.

Yes, we have rewritten the paragraph to clarify computation of canopy height and justify the decisions made to simplify the structure of the system (lines 155-165). This simplification is based on the homogeneity in composition of the tree stratum of the dehesa, dominated by mature Quercus ilex sp., and on the very high variability of herbaceous species with low heights of the grassland canopy. To compute hc a constant height of 8 m has been assigned to oak trees, which is multiplied by its ground coverage in each pixel. The oaks fc is computed annually using summer NDVI in eq.8. During the summer the grasslands are dry, and the only photosynthetically active vegetation contributing to the NDVI signal are the oak trees. The grassland height is low (< 1 m), affecting the effective canopy height of each pixel less than that of the trees, and it is also difficult to compute based on monthly vegetation indices given the high species variability. For this reason, the grassland height has been discarded and only the contribution of trees was considered to compute hc. We are aware that this is a simplification of a complex system that will contribute to the error of modelled fluxes. However, it was an operative solution considering the scale of this study.

L131-132: Leaf area index was previously defined as L in L116 but here uses the acronym LAI. Should be consistent throughout the manuscript.

Yes, it has been corrected (line 203)

L151-153: Review sentence with more direct language. E.g. 'The good correspondence between the model input was verified [. . .]'

It be changed to: "In both cases, the good correspondence between the model input and the ground measurements was verified (data not shown)." (lines 208-209).

Section 2: Some more clarification is needed in the methodology section on how the model inputs and parameters were set up and evaluated. Perhaps also a table that states all the inputs and parameters used in SEBS with their values/method would help clarify this. This information is scattered in the text but should be directly and clearly stated in the methods. Were the input datasets filtered for cloud cover/quality? Looking at Table 1, the different datasets used have different temporal and spatial resolutions (additionally in the text it says MODIS LAI product was used but it is not shown in Table 1). So how were these datasets homogenized? Which resampling algorithm was used? Was everything averaged for the month? Was only daytime meteorological data used or also nighttime? All this information should be stated so that the presented method is reproducible. In addition, the model evaluation method, and criteria (e.g, RMSE, R2 etc) should be explicitly stated in this section.

The methodological section 2 has been reformulated to include the missing information about the application of the model described in the referee's comment. A new subsection "2.2 Model parametrization and dataset preparation" include all the missing information about the obtention and processing of model inputs and parameters. We have completed table 1 to account for all inputs, including LAI and *fc*, which were derived from MODIS NDVI, and no specific MODIS product were used for these variables. This is clearly detailed now in the new Table 1. It is also described in 2.2 section the use of monthly data, and that all datasets were spatially averaged or subdivided to a common resolution of 0.05°. In addition, information about the model evaluation and definition of criteria has been added to the end of the validation section (lines 214-216), renamed to "2.3 Validation sites and model evaluation".

L186: MBE acronym was not defined.

MBE stands for Mean Bias Error and it is defined now in the text, (line 215).

L202-204: review sentence 'A few of the years [..] an increase in run-off'

It will be changed to: "Very wet years, and those with average rainfall but intense precipitation events producing an increase in run-off, did not follow this pattern." (line 280-281).

L218: Here it is mentioned that drought was evaluated at the annual scale but how was it aggregated? As an annual average or cumulative over the year?

The annual value was an average of monthly anomalies. This information was added to the revised version in lines 241-242.

L222-223: why is the drought event of 2016/2017 considered mild, if it reaches similar levels as the years 2004/2005 and 2011/12, which were considered the most severe droughts (Fig.4)? Is there a cutoff/threshold?

Yes, we have defined drought intensity in terms of the maximum negative anomaly of relative ET values reached during the event (thus using the standard deviation as a measure of its departure from the mean). When analyzing the events occurred during the study period, the following thresholds were used: severe drought (anomalies <=-1.5); moderate drought (anomalies between -1 and -1.5) and mild drought (anomalies between -1 and 0). These classes are used for both annual and monthly time steps. These definitions have been included in the description of the methodology (lines 245-247). In terms of intensity, only the drought event of 2004/2005 can be considered severe (max negative anomaly = -1.7) and 2016/2017 is classified as moderate with the maximum negative anomaly equal to -1.29.

L225-228: Review sentence 'Figure 5 aggregates [..] scarcity on the system'. Sentence is too long, maybe cut in two with more direct language.

The sentence will be changed to: "Figure 5 aggregates, for the total dehesa area, the evolution of the relative ET anomalies, together with the exchanges of energy between the surface and the atmosphere, the green canopy cover, and the production of rainfed wheat. The last two variables were selected as indicators of the impact of water scarcity on the system." Lines (305-309)

L263-264: Make sentence more direct 'The duration [. . .] these periods'.

As drought intensity and duration have been defined in the methodology (see a previous answer), the sentence has been shortened, lines 344-345.

Section 3.2: It would maybe be interesting to do a trend analysis to investigate if drought events are becoming more frequent/severe? Probably the time series is not large enough... but it does seem that the there are slightly more negative anomalies (particularly for Sta. Clo) from 2013/2014 onwards.

This is an interesting analysis that we would like to perform when a longer dataset is available. The current database, as the reviewer mentioned, is not large enough and it could provide misleading information.

L293: More direct language, e.g. 'The SEBS model was used [..]'.

The sentence of L293 has been changed (line386).

L317-19: Review sentence. More direct language, e.g. 'The approach proved useful [..] defining and identifying areas of interest for future studies at finer resolutions'.

The sentence is changed to: The approach proved useful for providing insight into the characteristics of drought events over this ecosystem, and for defining and identifying areas of interest for future studies at finer resolutions, (lines 410-412).

Table 1: In table caption, it says from 2000-2015 but the study time period is 2001-2018 right?

Yes, it was a mistake, it’s 2001-2018 and has been corrected in the manuscript.

Figure 6: The dehesa area of interest should be made more explicit and clearer in the map and legend. Also, little spatial analysis was provided in the text. For example, there seems to be important differences and patterns in the northern tip compared to the rest of the area of interest, most clearly seen in the average ET/ET0 map or in 2004/05, 2008/09, and 2011/12.

We have modified Figure 6 to highlight the dehesa area in the figure and the legend. Regarding the spatial analysis, the comment in the text is indeed very reduced, since we have not performed a detailed analysis yet. Some differences can be observed visually but without a more careful analysis, we preferred to include only a general comment related to the experimental site's areas where we have better information.

Figure 7a: There is no legend for the dashed green line.

The explanation has been added to the caption of Figure 7 (line 608)

All figures: There should be self-explanatory captions in all figures so that the reader can understand the figure without looking at the main text.

The figure captions have been reviewed (lines 594-612)

Long-term water stress and drought ~~monitoring~~ assessment of Mediterranean oak savanna vegetation using thermal remote sensing

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Abstract. Drought is a devastating natural hazard that is~~,~~ difficult to define, detect and quantify. The increased availability of both meteorological and remotely sensed data provides an opportunity to develop new methods to identify drought conditions and characterize how it changes over ~~Global meteorological data and remote sensing products present new opportunities to characterize drought in an objective way, and to extend this analysis in~~ space and time. In this paper, we applied the surface energy balance model SEBS (Surface Energy Balance System) for the period 2001-2018, to estimate evapotranspiration and other energy fluxes over the *dehesa* area of the Iberian Peninsula, with a monthly temporal resolution and 0.05º pixel size. A satisfactory agreement was found between the fluxes modelled and the measurements obtained for three years by two flux towers located over representative sites (RMSD = 21 W m^{-2} and R^2 = ~~of~~ 0.76, on average for all energy fluxes and both sites). The estimations of the convective fluxes (LE and H) showed higher deviations, with RMSD = 26 W m^{-2} on average, than Rn and G, with RMSD = 15 W m^{-2}. At both sites, annual ET was very close to total precipitation with the exception of a few wet years in which intense precipitation events, producing high run-off, were observed. The analysis of the anomalies of the ratio of evapotranspiration (ET) to reference ET (ET$_o$) was used as an indicator of agricultural drought on monthly and annual scales. Hydrological years 2004/2005 and 2011/2012 stood out for their negative values. T~~, with t~~he first one was~~being~~ the severest of the series, with the highest ~~the~~ impact observed on vegetation coverage and grain production. On a monthly scale, this event was also the longest and most intense, with peak negative values in January-February and April-May of 2005, explaining its great impact on cereal production (up to 45% reduction). During the drier events, the changes in the grasslands and oak trees~~vegetation~~ ground cover ~~over the months, with a preponderant presence of grasslands compared with those in which only oak trees were active,~~ allowed a separate analysis of the strategies adopted by the two strata to cope

with water stress. These results indicate that the drought events characterized for the period did not cause any permanent damage on the vegetation of *dehesa* systems. The approach tested has proved useful to provide insight into the characteristics of drought events over this ecosystem and will be helpful to identify areas of interest for future studies at finer resolutions.

1 Introduction

Drought, which is a devastating natural hazard and~~,~~ globally widespread, has~~and with~~ complex consequences across spatio-temporal scales and sectors. Unlike other disasters, it is still a challenge to define, detect and quantify droughts (Sheffield and Wood, 2011), impeding most prevention and mitigation actions. When droughts affect savannas, the two canopies of this ecosystem, grasslands and trees/shrubs, suffer from different stresses: (i) the pasture production is reduced or lost, with a direct economic consequence resulting from the need to supplement animal feeding and, in more severe situations, the death or premature sale of animals; (ii) the decline and dieback of trees affect the ecosystem structure, jeopardizing the long-term conservation of the system (Fenshan and Holman, 1999). Traditional agropastoral systems in arid and semiarid areas have developed strategies to cope with drought, such as diversifying into crops and livestock, into animal species and breeds, or fluctuating herd sizes (Hazell et al., 2001). More recently, insurance services for damage caused by water stress to pasture production provide farmers with a means for recovery after a disaster. However, the slow ~~-~~onset ~~nature~~ of drought, the large extension of savanna areas and their complex canopy structure pose additional difficulties to the already challenging monitoring of drought and its damage assessment.

The increasing availability of global meteorological data and new remote sensing products, with advanced processing services and free and open data, offers an opportunity to characterize drought objectively, and to extend its analysis in space and time. Many indicators of drought using remote-sensing inputs have been developed in the last decades (Wardlow et al., 2012). Surface energy balance models (SEBM) provide a physically based rationale to combine the most often used remote-sensing retrievals for drought monitoring: vegetation indices (VIs) and land surface temperature (LST). The VIs provide information about the amount and condition of the vegetation (Jackson and Huete, 1991), while the land surface temperature describes the state of the surface and the partitioning of the available energy into sensible heat (H) and latent heat (LE) or evapotranspiration (ET) (Kustas and Norman, 1996). SEBM ~~LST and VIs combined in SEBMs~~ have been used to provide~~provided~~ ET ~~accurate~~ estimations~~ of ET~~ over agriculture (Anderson et al., 2015; Allen et al., 2011; Cammalleri et al., 2012; Andreu et al., 2015; Gonzalez-Dugo et al., 2009, 2012) and agroforestry systems (Andreu, 2018a,b; Guzinski et al. 2018; Carpintero et al. 2016). In particular, the SEBS (Surface Energy Balance System) model (Su, 2002) presents a good compromise between the detailed parameterization of the turbulent heat fluxes for different states of the land surface on the one hand, and the input requirements, kept to a feasible minimum and without requirements for local calibration. The evapotranspiration of a canopy is a suitable indicator of its water status and a good measurement of the impact of water shortage on vegetation and on the ecosystem functioning. Evapotranspiration and soil moisture anomalies have been widely used for spatially distributed monitoring of agricultural drought (Anderson et al., 2016; Cammalleri el al., 2015; Sheffield et al., 2004). These anomalies underline the abnormally dry conditions when compared to the usual state of an ecosystem, derived from historical data. Evapotranspiration anomalies were used here to ~~monitor~~ assess drought and vegetation water stress over the holm oak savanna area of the Iberian Peninsula during a period of seventeen years.

The Mediterranean oak savanna, called *dehesa* in Spain and *montado* in Portugal, is the most extensive and representative agroforestry system in Europe, with more than 3 million hectares in the Iberian Peninsula (Moreno and Pulido, 2009). It is a man-made ecosystem that maintains a fragile balance between its multiple uses (livestock, cereal crops, cork, hunting, etc.) and the conservation of its natural resources. The *dehesa's* diversity of habitats, giving refuge to a large number of species (Díaz et al., 1997), is especially recognized, and it is listed as having community-wide interest in the EU habitat directive (92/43/EEC). It is a water-controlled system, with its productivity directly dependent on water availability. Mediterranean oaks have the ability to dampen the effects of water scarcity through a complex combination of drought resistance mechanisms with different time scales, as shown by Rambal (1993) for *Quercus coccifera L*. However, an additional problem to the recurrent water scarcity, is the identification of low soil water content as an initiating factor involved in the severe oak decline affecting a large area of *dehesa* since the early 1980s (Sánchez et al., 2002). Drought events impede the growth of *Q~~.~~uercus ilex* seedlings and increase their susceptibility to *Phytophthora cinnamomic* (Corcobado et al., 2014), the main biotic factor responsible for this decline (Sánchez et al., 2002).

Similarly to other savanna ecosystems, the different components of *dehesa* structure~~:~~ (sparse tall vegetation, large areas of grasses, shrubs, and bare soil), contribute differently to the turbulent exchange and radiative transfer, hindering its modeling especially when compared with more homogeneous landscapes. In addition, these vegetation layers differ in phenology, physiology and function: while most trees are evergreen and have access to deep sources of water all year, the herbaceous layer only taps water from the first cm of soil and dries up during summer. The combined different functioning and characteristics of the system components affects the exchange of sensible and latent heat flux, resulting in a high spatial and temporal flux variability difficult to account for in model parametrization and algorithms. This structure appears to play an important role in savannas' resilience, making the system an efficient convector of sensible heat and keeping the canopy surface temperature inside the adequate range for survival (Baldocchi et al., 2004).

In this work, a surface energy balance model, SEBS (Surface Energy Balance System) (Chen et al., 2013, Su, 2002) has been applied to estimate evapotranspiration and other energy fluxes from 2001 to 2018 over the *dehesa* areas of Spain and Portugal. A first objective was to validate the energy fluxes produced by this model over the *dehesa* landscape. The second was to analyze the anomalies of the ratio of ET to reference ET as an indicator of agricultural drought in this environment at monthly and annual scales and use it to characterize the main drought events occurring in this period in space and time.

2 Data and methodology

The study was conducted over the oak savanna area of the Iberian Peninsula (Figure 1) using data from January 2001 to August 2018. This ecosystem covered 3.12 million ha in 2006 according to the European CORINE Land Cover inventory (CLC2006. 100 m - version 12/2009 https://www.eea.europa.eu/data-and-maps/data/ clc-2006-raster-4). The area has remained fairly stable during the study period, with changes of less than 1.5% between CLC2006 and the previous and posterior inventories, in 2000 and 2012.

2.1 SEBS model description~~ and application~~

A revised version of the surface energy balance system model known as SEBS (Su, 2002~~; Chen et al., 2013~~) was used to estimate land heat fluxes integrating remote sensing and meteorological forcing data~~. The new parameterization of the bare soil excess resistance to heat transfer, included in the revised version, improved the model's performance especially for bare soil and low canopy surfaces (Chen et al., 2013)~~. A~~-~~ brief description of the model is presented below (for further discussion, see Su, 2002 and Chen et al., 2013). The latent heat flux (LE) was computed as a residual of the surface energy balance equation:

LE~~Rn~~ $= Rn - G -$ ~~+~~H ~~$+ LE$~~ ,
(1)

where Rn is the net radiation, G is the soil heat flux and H is the turbulent sensible heat flux. The net radiation is calculated with the following equation:

$$R_n = (1-\alpha)SW_d + \varepsilon LW_d - \varepsilon\sigma LST^4 \tag{2}$$

Where α is broadband albedo; SW_d is the downward short-wave radiation; LW_d, the downward long-wave radiation; ε, the land surface emissivity; σ, the Stefan-Bolzmann constant; and LST, the land surface temperature.
The soil heat flux is derived from its ratio to the net radiation (Γ) using equation 3:

$$G = R_n[\Gamma_C + (1-f_C)(\Gamma_S - \Gamma_C)] \tag{3}$$

This ratio is assumed to be equal to 0.05 (Monteith, 1973) for surfaces with fully covered vegetation (Γ_C) and 0.315 for bare soils (Γ_S) (Kustas and Daughtry, 1990). The green canopy cover, f_c, is determined using the normalized difference vegetation index (NDVI) in equation 8.

Using equations 1 to 3 and energy balance considerations at limiting cases, the following reductions can be applied: (i) under the dry limit (equation~~s~~ 4~~ and 5~~), the evapotranspiration~~ is assumed to become zero~~, λE_{dry} is assumed to become zero due to the limitation of soil moisture and the sensible heat flux, H_{dry}, is at its maximum,~~;~~ ~~H_{dry}.~~

$$\lambda E_{dry} = R_n - G \quad - H_{dry} \equiv 0 \tag{4}$$

~~$H_{dry} = R_n - G$ (5)~~

(ii) under the wet limit (equations 5~~6~~ and 6~~7~~), the evaporation takes place at potential rate, λE_{wet}, ~~is~~ only limited by the available energy at the given surface and atmospheric conditions. ~~, λE_{wet}, and~~ T~~t~~he sensible heat takes its minimum value~~-~~, H_{wet}, with ~~:~~the internal resistance of the Penman-Monteith combination equation in the form written by Menenti (1984), $r_i \equiv 0$, by definition.

$$\lambda E_{wet} = R_n - G \quad - H_{wet} \tag{5~~6~~}$$

$$H_{wet} = \left((R_n - G) - \frac{\rho C_p}{r_{ew}} \cdot \frac{e_s - e}{\gamma} \right) \Big/ \left(1 + \frac{\Delta}{\gamma} \right) \cancel{R_n - G - \lambda E_{wet}}$$

(6~~7~~)

where ρ is the density of air; C_p the specific heat at constant pressure; e and e_s are actual and saturation vapor pressure respectively; γ is the psychrometric constant, Δ is the rate of change of saturation vapor pressure with temperature and r_{ew} is the external or aerodynamic resistance. The sensible heat is computed according to the Monin-Obukhov similarity theory and limited by the dry and wet conditions. ~~H_{dry} is given by equation 5 and H_{wet} is derived using equation 7 and the application of a set of assumptions for extremely wet conditions to the Penman-Monteith equation (Menenti, 1984).~~ A complete description of the model and the use of the dry and wet limits can be found in Su (2002).

2.2 Model parametrization and dataset preparation

~~The model was applied over the entire Iberian Peninsula using monthly data with a spatial resolution of 0.05°. Satellite and meteorological data sources are described in Table 1. Albedo, land surface temperature (LST), surface emissivity and leaf area index (LAI) were derived from different products of MODIS sensor. Meteorological data were provided by the ERA-Interim, a global atmospheric reanalysis data set from the European Centre for Medium-range Weather Forecast.~~

For the application of SEBS over *dehesa* area ~~The parametrization of~~ two surface variables, f_c and the height of the canopy (h_c), has been adapted to the specific characteristics of this ~~*dehesa*~~ ecosystems.~~-~~ The green canopy cover (f_c) and leaf area index (L) were calculated using the following equations (adapted from Choudhury et al., 1994):

$$f_c \cancel{(1 - f_c)^{\xi}} = 1 - \left(\frac{NDVI_{max} - NDVI}{NDVI_{max} - NDVI_{min}} \right)^{\frac{1}{\xi}} \cancel{\frac{NDVI_{max} - NDVI}{NDVI_{max} - NDVI_{min}}}$$

(7~~8~~)

$$\cancel{f_c} L = -\frac{1}{k} \ln(1 - f_c) \cancel{= 1 - \exp(-kL)}$$

(8~~9~~)

where $NDVI_{max}$ and $NDVI_{min}$, represent a surface fully covered by vegetation (~0.94) and completely bare (~0.15), respectively. The parameter ξ represents the ratio of the canopy extinction coefficient (K') to a leaf angle distribution term (k). k was assumed to be equal to 0.5 for a random distribution of leaves, as the ecosystem contains erectophile grasses and planophile oak tree leaves (Andreu et al., 2019). K' adopted a value of 0.8 obtained from experimental data and within the range proposed for

NDVI by Baret and Guyot (1991). NDVI data was provided by MODIS instrument, averaging the 16-day original product to monthly scale.

The height of the canopy was computed to account for variations in the tree component. This variable is needed for calculating the momentum roughness length and thus, important for the sensible heat calculation. ~~,~~The tree stratum of the *dehesa* is quite homogeneous in composition, dominated by mature *Quercus ilex sp*., and grassland canopy has a very high variability of low height herbaceous species. Considering these reasons, the ecosystem structure has been simplified to compute hc in the following way: A constant height of 8 m has been assigned to oak trees, which is multiplied by its ground coverage in each pixel. Oak *fc* is computed annually using summer NDVI in eq. 7. During the summer the grasslands are dry, and the only photosynthetically active vegetation contributing to the NDVI signal are the oak trees. The grassland height is low (< 1 m), affecting the effective canopy height of each pixel less than the trees, and it is also difficult to computed based on monthly vegetation indices given the high species variability. For this reason, the grassland height has been discarded and only the contribution of trees was considered to compute h_c. This simplification of a complex system certainly may contribute to the error of modelled fluxes. However, it was an operative solution considering the scale of this study.

SEBS model was originally designed for instantaneous applications. Monthly calculations using the same model were demonstrated by Chen et al. (2014). The structure of the model was not changed, and the implementation differed in the input datasets. The model was applied over the entire Iberian Peninsula with a spatial resolution of 0.05° and a monthly input dataset. Satellite and meteorological input datasets are described in Table 1. All datasets were spatially averaged or subdivided to a common resolution of 0.05°.

The land surface temperature (LST) was provided by MODIS instrument, using the monthly mean of day and night LST product, which provides the most complete coverage. The accuracy of this product, a key variable in SEB models, was evaluated by Chen et al. (2017), supporting its applicability for climate studies and numerical model evaluation.

Meteorological data were provided by the ERA-Interim, a global atmospheric reanalysis data set from the European Centre for Medium-range Weather Forecast (ECMWF). Monthly means of daily means were produced by ECMWF as the average of the four main synoptic monthly means at 00, 06, 12, and 18 UTC. The forecast model, data assimilation method, and input datasets used to produce ERA-Interim can be found in Dee et al., (2011) and a description of the product archive in Berrisford et al., (2011).

~~with a greater influence on the average height of the system than short and more variable pasture. An annual value of canopy~~ ~~h_c~~ ~~was estimated for every pixel during the summer, when oaks are the only green vegetation contributing to the pixel spectral response. An effective value of~~ ~~h_c~~ ~~for the year was estimated based on the tree coverage, assessed using the summer value of the NDVI, and an average tree height of 8 m, representative of the predominant tree species *Quercus ilex sp*.~~

~~The model was applied over the entire Iberian Peninsula using monthly data with a spatial resolution of 0.05°. Satellite and meteorological data sources are described in Table 1. Albedo, land surface temperature (LST), surface emissivity and leaf area~~

~~index (LAI) were derived from different products of MODIS sensor. Meteorological data were provided by the ERA-Interim, a global atmospheric reanalysis data set from the European Centre for Medium-range Weather Forecast.~~

To analyze model results, the monthly rainfall gridded data of the Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 (Harris et al., 2014), provided by the Global Climate Monitor System (Camarillo-Naranjo et al., 2019), have been averaged over the *dehesa* area of the Iberian Peninsula.

2.3~~2~~ Validation sites and model evaluation

Two experimental sites (Figure 1) with similar flux measurement instrumentation have been used to validate the evapotranspiration and other energy fluxes estimated using the SEBS model.~~ Detailed information on the measurements and the processing of the data can be found in Andreu et al. (2018a and b).~~ Both eddy covariance towers, named Sta.Clo (Santa Clotilde, Andalusia, 38°12′N; 4°17′W, 736 m a.s.l.) and ES-LMa (Boyal de Majadas del Tiétar, Extremadura, 39°56′N; 5°46′W, 260 m a.s.l.) are located over *dehesa*-type ecosystems under similar management and a landscape of scattered oak trees with a fractional cover of around 20%, in southern and southwestern Spain, respectively. The convective fluxes of the systems are measured above the tree height (at 17 m in Sta.Clo and 15 m in ES-LMa) with closure balance errors of 20% and 14%, both values being within the range found by other authors (Foken, 2008; Franssen et al., 2010). For ES_LMa the processing of the data corresponded to the procedure standardized by Fluxnet network ((https://fluxnet.org/). For Sta.Clo, d~~D~~etailed information on the measurements and the processing of the data can be found in Andreu et al. (2018a and b). In this case, the comparison period was selected attending to the quality of the data and some months (3 of 36) were discarded due to missing information. Soil moisture, precipitation and other complementary measurements of the vegetation (reflectance, L~~AI~~, green canopy cover) were used to characterize the dynamics of the vegetation and the soil water status throughout the year.

The area contributing most to the fluxes measured was estimated by using Schuepp et al. (1990) and varied between 1 and 2 km. These footprints are lower than the pixel size of 5 km used for the application of the SEBS model. However, the homogeneity of the system, with similar tree ground cover fraction and pasture management at several kilometers around the towers supported the capacity of these sites to serve as a reference for the validation of modelled fluxes. ~~Also verified I~~in both cases, ~~was~~ the good correspondence between the model input meteorological data at the tower's location and the ground measurements was verified (data not shown).

Monthly rainfall data for the seventeen years of the study was provided by the closest weather station to each site, located at 3 km and 16 km of Sta.Clo and ES-LMa towers, respectively. Both of them are operated by the Spanish Meteorology Agency (AEMET).

Model performance was quantified via the root- mean-square-difference (RMSD) and the coefficient of determination (R^2) between the modeled and observed fluxes. In addition, the mean- bias-error (MBE), computed by taking the difference between predicted and observed, was used to assess model under- and over-estimations.

2.3 Water stress calculations

The relative evapotranspiration is the ratio of actual to potential or reference ET (ET/ET_o). It has been used as an indicator of crop water stress (Anderson et al., 2015, 2016), of drought (Anderson et al., 2011), and as a proxy for soil moisture (Su et al., 2003). The same approach is used worldwide in irrigation engineering to compute crop water requirements following FAO (24 and 56) guidelines (Doorenbos and Pruitt, 1977; Allen et al, 1998). The reason to normalize by ET_o is to separate the ET signal component responding to soil moisture from variations due to the available energy. Anderson et al., (2011) showed that anomalies in ET/ET_o were more strongly correlated with other drought indices than were anomalies in ET for most US climatic divisions, showing strong agreements in the southwest of the country, with a similar climate than the study area. The comparison of both variables anomalies has been also performed here.

Anomalous water stress conditions indicating drought were assessed here with the standardized values of relative ET. FAO56 reference ET (Allen et al., 1998) was selected to estimate the atmospheric evaporative demand (AED), given the difficulties of reproducing the biological control of the transpiration, even at potential rates, of the different types of vegetation conforming this ecosystem.

The vegetation water stress caused by the long dry summers of the Mediterranean climate can be considered to be the 'normal' state of the system for several months of the year. To identify unusually dry conditions indicating drought, standard (z) scores of this variable (ET/ET_o) for a given month/year have been computed. This standardization procedure assumes that the data follow a normal distribution. Some authors (Sheffield et al., 2004; Cammalleri et al., 2015) have pointed out that soil moisture and the water deficit index derived from it are generally characterized by a skewed distribution and can be statistically better represented using the beta distribution. In this case, the analysis of ~~the analysis of the~~ ET and relative ET monthly ~~time series~~ histograms (shown in the supplement) indicated ~~that even when~~ that most months presented an approximately symmetric distribution, with skewness between -0.5 and 0.5 for both variables, three of them were moderately skewed and only one month (for ET) and two months (for ET/ETo) were slightly above one~~the histograms of both time series followed a skewed distribution, more pronounced in the case of the actual than the relative ET,~~ ~~, the values of mean, median and mode of the relative ET series were very similar,~~ backing up the use of z scores for the standardization of this variable. Annual drought analyses were performed by averaging monthly anomalies.

Drought intensity is defined here in terms of the maximum negative anomaly of relative ET values reached during an event (thus using the standard deviation as a measure of its departure from the mean) and the drought event duration as the successive number of months with negative anomalies. To classify the events occurred during the study period, the following thresholds have been used: severe drought (anomalies <=-1.5); moderate drought (anomalies between -1 and -1.5) and mild drought (anomalies between -1 and 0). These classes are used for both annual and monthly time steps.

Two variables, vegetation coverage (f_c) and rain-fed wheat production, have been selected as drought impact indicators. The vegetation condition and the failure of crops are known consequences of a declining soil moisture and both have been used previously as indicators of drought (Liu and Kogan, 1996; FAO, 1983). Winter cereals are the main cropping system of these areas, in which the low fertility of the soils does not allow a more intense agricultural use. ~~.~~ Its growth cycle is similar to that of the natural grasslands, with both of them escaping drought and coping with the long summer dry season by completing its life cycle before serious soil and plant water deficits develop. Given that no irrigation is provided, the impact of moisture deficits over its yield can be consider an indirect indicator of the impact of drought on *dehesa* herbaceous vegetation. Annual yield statistics (http://www.mapama.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/) have been gathered and aggregated for the *dehesa* area (Figure 1).

3 Results and discussion

3.1 Model validation

The comparison of SEBS model estimation of monthly energy fluxes with measurements at the two EC towers during a total of six years, 2009 to 2011 for ES-LMa and 2015 to 2017 for Sta.Clo, displayed in Figure 2, ~~presented a~~ generally showed good agreement, with an average root mean square difference (RMSD) of 21 W m^{-2} and R^2 of 0.76, for all energy fluxes and both sites. The estimations of the convective fluxes (LE and H) show higher deviations, with RMSD =26W m^{-2} on average, than Rn and G, with RMSD = 15 W m^{-2}. Model performance at ES-LMa site was, in general, superior to that at Sta.Clo, with all the statistics metrics computed for the comparison (RMSD, MBE and R^2) presenting lesser dispersion and slightly lower errors. LE was slightly overestimated at both sites (MBE =10.3 and 2.8 W m^{-2} at Sta.Clo and ES-LMa, respectively), which is in agreement with previous applications of the model (Michel et al., 2016). This overestimation was particularly significant for some springtime months at Sta.Clo, when the sensible heat was underestimated by the SEBS model (Chen et al., 2019). However, LE estimations presented a similar or lower RMSD than other applications of the SEBS model (Chen et al. 2014; Vinukollu et al, 2011). In particular, the work by Chen et al. (2014) estimated energy fluxes over China at the same temporal scale and with similar input databases. The comparison with measurements at 11 Chinese flux towers presented results that were very close to the ones obtained by this application. Mean RMSDs for all fluxes were alike (RMSD = 22 W m^{-2} was reported by Chen et al. (2014)), with a marginally better performance for convective fluxes and a poorer one for Rn and G (RMSDs in China were 22 and 24 W m^{-2} for convective fluxes and, Rn and G, respectively).

Figure 3 presents the evolution of modelled ET and ET_o, ET/ET_o and measured precipitation from 2001 to 2018, aggregating the hydrological year (between October 1st and September 30th) at the two experimental sites. It can be observed that annual ET variations for the period followed a similar pattern of precipitation at both sites, confirming the predominant control of water availability over the evaporation in these systems. This control is consequently extended to ecosystem productivity and in most years the water consumption, coupled to biomass production, is close to the total rainfall. Tree density is similar at both sites and the differences in water consumption between them are explained by variations in annual pasture production, due to differences in water availability and soil properties. Very wet years, and those with average rainfall but intense precipitation events producing an increase in run-off, did not follow this pattern.~~A few of the years are outside this pattern relating rainfall and ET; this corresponded either to very wet ones, or to years of average rainfall but with the occurrence of intense precipitation events that produced an increase in run-off.~~ This can be observed by the run-off recorded at Sta.Clo watershed reservoir (Figure 3a). The main land-use of this small watershed (48.4 km^2) is *dehesa*, but other uses can be found as well, such as olive orchards and field crops. ~~Very low runoff values are recorded in regular and dry years, with peaks for the wet ones.~~

Annual run-off measurements followed a close relationship (data ~~not~~ shown in the supplement, Figure S2) with the annual aridity index (Budyko, 1974) estimated at Sta.Clo following Arora (2002), as the ratio between potential evaporation and annual precipitation. On average, we found aridity indices of above one at both sites, indicating dry regions where the evaporative demand cannot be met by precipitation. In this case, AED was computed using Penman-Monteith for comparison purposes. Sta.Clo site is noticeably less arid than ES-LMa, with an aridity index equal to 2.9 and 3.75 on average for the 17 hydrological years at Sta.Clo and ES-LMa, respectively, with both of them falling under the category of a semi-arid climate regime (Ponce et al., 2000). The two sites presented similar annual ET_o values for the period (Figure 3~~4~~), but annual precipitation was around 200 mm higher, on average, at Sta.Clo, with a higher and more variable ET/ET_o throughout the years. What can also be observed in Figure 3 is the complementary relationship between actual and reference evapotranspiration at this temporal scale, with the sum of annual ET and ET_o approaching a constant value at both sites, confirming previous hypotheses (Bouchet, 1963; Morton, 1975; Brutsaert and Stricker, 1979).

3.2 Annual drought monitoring and impact assessment

Drought was characterized on an annual scale over the experimental sites and the whole area of the *dehesa* of the Iberian Peninsula using the relative evaporation anomalies. Figure 4 presents their evolution for the two sites throughout the study period. A clear similarity can be observed in the main negative anomalies, which identify the most severe droughts during the years 2004/05 and 2011/12 at both sites, despite the differences in aridity and the distance (Figure 1) between them, indicating the extended area and intensity of both events. Differences are more evident in the case of the mild droughts, occurring at both sites but with different intensities during two periods, 2007 to 2009 and 2016 to 2018.

When the whole *dehesa* area is considered (Figures 5 and 6), a more complete view of the general intensity, impact, and spatial distribution of those dry periods, can be obtained. Figure 5 aggregates, for the total *dehesa* area, the evolution of the relative ET anomalies, together with ~~variables related to~~ the exchanges of energy between the surface and the atmosphere, the green canopy cover, and the production of rainfed wheat. ~~, t~~The last two variables were selected as indicators of the impact of water scarcity on the system.

The two severely dry years identified at the experimental sites were the driest ones for the entire *dehesa* area, with 2004/2005 standing out as the most severe event of the time series. None of them lasted more than one year. For these two dry years, a reduction in the latent heat can be observed when compared to the complete series, producing a swap with the sensible heat in the second position in magnitude of the energy balance components. A rise in the surface temperature, increasing the difference with the air temperature, is also observed for those dry years. The order of severity in dryness, established by the magnitude of negative values of ET/ET$_o$ anomalies, is also observed in their impacts over the system (Figure 6). In 2004/05, the wheat production in the area was reduced by almost half of the average (45%) for the period analysed, and the vegetation groundcover fraction fell by 20% compared to the average of the same period. This severe drought affected the entire Iberian Peninsula, with the Spanish and Portuguese cereal and hydroelectricity productions decreasing by 40% and 60% with respect to the average (Garcia-Herrera et al., 2007) and a 10% reduction in total EU cereal yields (UNEP, 2006). The event during 2011/2012 was among the largest and most severe ones in Europe for the 18-year simulation period analysed by Cammalleri et al. (2015), contributing to a global decline in grain production.

Figure 6 shows maps of ET/ET$_o$ anomalies in Iberia for the seventeen years of the study, highlighting the *dehesa* area of interest in this work. The spatial variability of these anomalies for most years is significant, although prevalently dry and wet years can be distinguished. In 2004/05 and 2011/12, the drought was severe and affected most of the area of interest, as the aggregated values of Figure 5 also point out. In 2008/09, the water stress was milder in the western area, as can be observed in Figure 6, as at the experimental site of Sta.Clo (Figure 4) located in this part of the region. The recovery of the vegetation water status was generally achieved the year following the dry one in most areas.

3.3 Monthly drought analysis

The monthly evolution of relative evapotranspiration anomalies is displayed in Figure 7a, with negative values indicating water stress conditions highlighted in red. Absolute ET and ET$_o$ values, used to calculate these anomalies, are shown in Figure 7b together with monthly rainfall for the period. One can observe the alternation of complementary and parallel characteristics of ET and ET$_o$ throughout the year, with the longest complementary period indicating water-limited ET conditions starting in May for most of the years, confirmed by the decreasing trend in rainfall starting in that month. At the end of the summer when the first rains arrive the trend of ET and ET$_o$ changes, producing a secondary peak in ET, much weaker than the one earlier in the year, that lasts until the energy-limited parallel phase starts in November. Both variables follow a concurrent rise from January until the soil water deficit limits ET again.

The annual fluctuations of the green canopy cover (thick green line in Figure 7a) followed the expected seasonality of Mediterranean vegetation, corresponding to the dynamics of ET and ET$_o$ changes. The maximum coverage (March and April) corresponds to the peak of grassland production (and ET although with different shape) and the minimum appears during the dry summer, only endured by the oak trees. In some years, the growing season presents a bimodal shape, with an initial peak produced by autumn pastures, which is also reflected in ET values. It can be observed mostly in wet years (e.g. 2003, 2007, 2011), with the vegetation growth following a pattern that can be related to the soil water availability, represented here by the ET/ET_o anomalies.

The duration and intensity ~~, in number of months with negative anomalies, and the intensity~~ of each drought event ~~can be quantified, which may~~ help to explain the response of the vegetation during these periods. In this sense, the two main drought events identified on an annual scale (2004/05 and 2011/12), presented dryer than normal conditions during the whole or most of the year. The first event was longer (sixteen months in the first case, prolonging the drought to the beginning of the following year) and with higher negative values than the second one, of an eleven-months duration, explaining the greater impacts detected on the vegetation and cereal yield. Other dry periods, in 2009, 2017 and 2018, presented consecutive negative anomalies for ten to eleven months but, in some cases, the non-homogeneous distribution of the drought observed in Figure 6, may have undermined the impact analysis on this aggregated spatial scale. In terms of impact assessment, the time of the year with peak negative anomalies is important, with springtime events producing greater impacts (e.g. in 2004/2005 the highest negative values corresponded to January, February, April and May of 2005).

During the dry years, the annual vegetation growth pattern varies with respect to the typical one, depending on the duration and severity of drought events. The dynamics of the vegetation in this system allows for a separate analysis of the effect of water scarcity over trees and pastures. The dashed green lines (Figure 7a) show the changes in annual maximum and minimum values of f_c, with the maximum ones mostly expressing the impact on pasture, and the changes in the minimum ones represent only the impact over the tree canopy. The decreases in pasture f_c are more pronounced than changes in oaks f_c, as grasslands are more abundant, and their roots are mostly located in the first centimetres of soil. On the contrary, the rooting system of the oak tree is in fact adapted to the regular dry periods of the Mediterranean climate, exploring a large volume of soil that can reach maximum values of around 5 m in depth and 30 m in horizontal extension (Moreno et al., 2005). The small decreases, observed in oaks f_c in Figure 7a during dry years, generally recovered within one or two years. This response of the tree leaf area is associated with low frequency oscillations, such as annual rainfall (Poole and Milles, 1981). This is also supported by the variance observed in f_c that can be explained by the anomalies of relative evapotranspiration of previous months. During the spring, the highest correlation coefficients are obtained for the previous two or three months (e.g. average f_c for the peak month, April, is correlated with average anomalies from February to April with an R^2 equal to 0.76 and with anomalies of the previous year with an $R^2 = 0.52$). However, during the summer, the coverage of the vegetation can be better explained by what has happened during the previous year (e.g. R^2 is equal to 0.39 for average August f_c and the anomalies of the two previous months, and 0.64 for the anomalies of the year), suggesting that those values of f_c might be linked to processes occurring at different time scales.

A more detailed analysis is required, but these results support the conclusion that the drought events characterized for this period did not cause any permanent damage to the vegetation, considering both the grasslands and the oak trees.

Similar results can be derived from the analysis of ET anomalies. Figure 8 presents a comparison of monthly anomalies of ET, ET/ET$_o$ and f_c. The anomalies of ET and ET/ET$_o$ showed a high similarity for the conditions of the study, with correlations of $R^2 = 0.76$ at monthly scale and $R^2 = 0.82$ at seasonal scale (results presented in supplement figures S3 and S4). It suggests that ET anomalies could be an option to monitor drought in *dehesa* areas. Nevertheless, the computation of ET$_o$ does not require additional variables than those already used by the energy balance models, with a quite straightforward computation. Once actual ET is estimated, the computation of ET/ET$_o$ takes very little effort and adds some confidence to the focus on the soil moisture signal. Regarding the evaluation of *fc* anomalies, it can be derived that the drought events identified using this variable would have been the same as using ET or ET/ET$_o$, but with different intensities and duration. The main differences can be found during the cold winter months when the vegetation is largely dormant. In these cases, the anomalies of *fc*, similarly to the performance of other indices based on vegetation as the Vegetation Condition Index (VCI) (Heim, 2002) have a limited utility. The results are more comparable and could be more useful during the growing season.

4 Conclusions

The SEBS model was ~~has been~~ used to estimate monthly energy fluxes over the *dehesa* area of the Iberian Peninsula from January 2001 to August 2018. There was a satisfactory agreement between modelled fluxes and measurements obtained for three years over two sites that are representative of the ecosystem.

At both sites annual ET was very close to total precipitation, with the exception of a few wet years and those in which intense precipitation events producing a high run-off were observed. Average aridity indices for the 17 hydrological years of 2.9 and 3.75 were computed at Sta.CLo and ES_LMa, respectively, indicating that their evaporative demand cannot be met by annual precipitation of these sites.~~, and the more arid conditions of ES_LMa.~~

Drought has been characterized on an annual and monthly scale over the experimental sites and the whole area of *dehesa* of the Iberian Peninsula using relative evaporation anomalies (ET/ET$_o$). At the annual scale, the negative anomalies of two years, 2004/2005 and 2011/2012, stood out during the study period at the experimental sites and the entire *dehesa* area. However, a recovery of average values is observed in the years following the dry ones, indicating the absence of prolonged droughts for the period. Maps of ET/ET$_o$ anomalies showed that most of the *dehesa* area was affected in those dry years. These maps complemented the averaged data, providing spatial information about regional impacts that could be useful for a more detailed analysis.

On the monthly scale, the drought event of 2004/05 is confirmed as being the longest, with sixteen consecutive months of negative anomalies (from October 2004 to January 2006), and the most intense event, with peak negative values in January-February and April-May of 2005, explaining the important impact on cereal production. The dynamics of the vegetation strata on a monthly scale allows for a separate assessment of water stress impacts on oaks and pastures. The different behaviour observed in vegetation ground cover during the drier events in months with a preponderant presence of grasslands, compared with months in which only oaks were active, is consistent with the different strategies adopted by the two strata to cope with water stress. In addition, the correlation of monthly vegetation fractional coverage with previous short or medium-term anomalies (from two months to one year) suggest that those values might be linked to processes occurring on a different time scale, depending on whether the grassland or the tree is the predominant vegetation.

These results back up the conclusion that the drought events characterized for this period did not cause permanent damage to the vegetation of *dehesa* systems, considering both the grasslands and the oak trees. The approach ~~tested has~~ proved ~~to be~~ useful for providing insights into the characteristics of drought events over this ecosystem, for ~~helping to~~ defining~~e~~ ~~the issues~~ and ~~for~~ identifying areas of interest for future studies at finer resolutions.

Code and data availability

SEBS code is available in GitHub repository to download (https://github.com/TSEBS/SEBS_Spain). Validation data of ES-LMa site is available at the European Fluxes Database Cluster (http://www.europe-fluxdata.eu/home/site-details?id=ES-LMa) and data of Sta.Clo site may be distributed on request to the principal investigator of Sta. Clotilde experimental site (M. P. González-Dugo, IFAPA, mariap.gonzalez.d@juntadeandalucia.es).

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Author Contributions

M.P.G.-D. conceived the original idea, analyzed the data and took the lead in writing the manuscript; X.C. and Z.S. designed the model, the computational framework, and contributed to the interpretation of the data; M.P.G.-D. and X.C. collected the input data and performed the numerical calculations; A.A., E.C., P.G.G. and A.C. collected and analyzed the validation data and reviewed the paper. All authors provided critical feedback and helped to shape the manuscript.

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Table 1. Input datasets used to calculate the surface energy fluxes over the Iberian Peninsula from 2000 to 2018~~5~~

Variable	Full variable name	Data source	Spatial resolution	Temporal resolution of input products	Method
SW_d	downward surface shortwave radiation	ERA Interim(ECMWF)[*]	0.7°~~80km~~	1 month~~6h~~	Reanalysis
LW_d	downward surface longwave radiation	ERA Interim(ECMWF)	0.7°~~80km~~	1 month~~6h~~	Reanalysis
T_a	air temperature	ERA Interim(ECMWF)	0.7°~~80km~~	1 month~~6h~~	Reanalysis
Q	specific humidity	ERA Interim(ECMWF)	0.7°~~80km~~	1 month~~6h~~	Reanalysis
u	wind speed	ERA Interim(ECMWF)	0.7°~~80km~~	1 month~~6h~~	Reanalysis
P	surface pressure	ERA Interim(ECMWF)	0.7°~~80km~~	1 month~~6h~~	Reanalysis
LST	land surface temperature	MOD11C3 V5[**]	0.05°	1 month~~1 month~~	Satellite
α~~*Albedo*~~	albedo	GlobAlbedo[***]/MODIS[**]	0.1°	1 month~~1 month~~	Satellite
NDVI	Normalized Difference Vegetation Index	MOD13C1 V5/MYD13C1 V5[**]	0.01°	16 days	Satellite
fc	fractional canopy coverage	Derived from NDVI using eq.7	0.01°	16 days	Satellite
L	leaf are index	Derived from *fc* using eq.8	0.01°	16 days	Satellite
hc	canopy height	Derived annually from summer NDVI	0.01°	16 days	Satellite

[*] http://apps.ecmwf.int/datasets/data/interim-land/type=fc/

[**] https://modis.gsfc.nasa.gov

[***] http://www.globalbedo.org/index.php

Figure Captions

Figure 1: Distribution of oak savanna area in the Iberian Peninsula. Location of Sta.Clo (Santa Clotilde) and ES-LMa (Las Majadas) validation sites and pictures of both eddy covariance flux towers.

Figure 2. Comparison of monthly energy fluxes of latent heat (LE), sensible heat (H), net radiation (Rn) and soil heat flux (G) estimated using the SEBS model at a monthly scale and observed fluxes at each oak savanna site: ES-LMa (LA) for the years 2009-2011 and Sta.Clo (SC) for the years 2015-2017.

Figure 3. Evolution of annual rainfall, ET, ETo and ET/ETo at ES-LMa site (a) and Sta.Clo site (b), and annual run-off at Sta.Clo watershed from the hydrological years 2001/02 to 2017/2018.

Figure 4. Annual anomalies of relative evapotranspiration at ES-LMa and Sta.Clo experimental sites estimated using the SEBS model from 2001/02 to 2017/18.

Figure 5. Evolution from 2001/02 to 2017/18 of annual anomalies of relative evapotranspiration, energy balance components, air and surface temperature, vegetation ground fraction cover and rainfed wheat yield, aggregated for the whole oak savanna area of the Iberian Peninsula.

Figure 6. Spatial distribution of annual anomalies of relative evapotranspiration for the oak savanna area of the Iberian Peninsula from 2001/02 to 2017/18, the average ET/ETo for the period and its standard deviation (STD)

Figure 7. (a) Monthly evolution of evapotranspiration anomalies (blue line) of the oak savanna area of the Iberian Peninsula from January 2001 to August 2018, with negative values indicating drier than normal conditions (depicted in red), and green canopy cover (green line). The dashed green lines connect the annual maximum and minimum values of *fc*; (b) Monthly evolution of and rainfall, ET_o and ET in the same region and time interval.

Figure 8. Comparison of monthly negative anomalies of ET, ET/ET_o and f_c for the entire oak savanna area of the Iberian Peninsula from January 2001 to August 2018.

~~Figure 1: Distribution of oak savanna area in the Iberian Peninsula. Location of validation sites and pictures of eddy covariance flux towers~~

~~Figure 2. Comparison of observed and estimated monthly energy fluxes using SEBS model during three years at each oak savanna site, ES-Lma (LA) and Sta.Clo (SC).~~

~~Figure 3. Evolution of annual rainfall, ET, ETo and ET/ETo at ES-LMa site (a) and Sta.Clo site, and annual run-off at Sta.Clo watershed from 2001/02 to 2017/2018 hydrological years~~

~~Figure 4. Annual anomalies of relative evapotranspiration at the experimental sites from 2001 to 2018.~~

~~Figure 5. Annual anomalies of relative evapotranspiration for the oak savanna area of the Iberian Peninsula from 2001/02 to 2017/18~~

~~Figure 6. Spatial distribution of annual anomalies of relative evapotranspiration for the oak savanna area of the Iberian Peninsula from 2001/02 to 2017/18, the average~~ ~~ET/ET_o~~ ~~for the period and its standard deviation (STD)~~

~~Figure 7. (a) Monthly evolution of evapotranspiration anomalies (blue line), with negative values indicating drier than normal conditions (depicted in red). and green canopy cover (green line) of the oak savanna area of the Iberian Peninsula. (b) Monthly evolution of and rainfall,~~ ~~ET_o~~ ~~and ET in the same~~

~~region and time interval~~

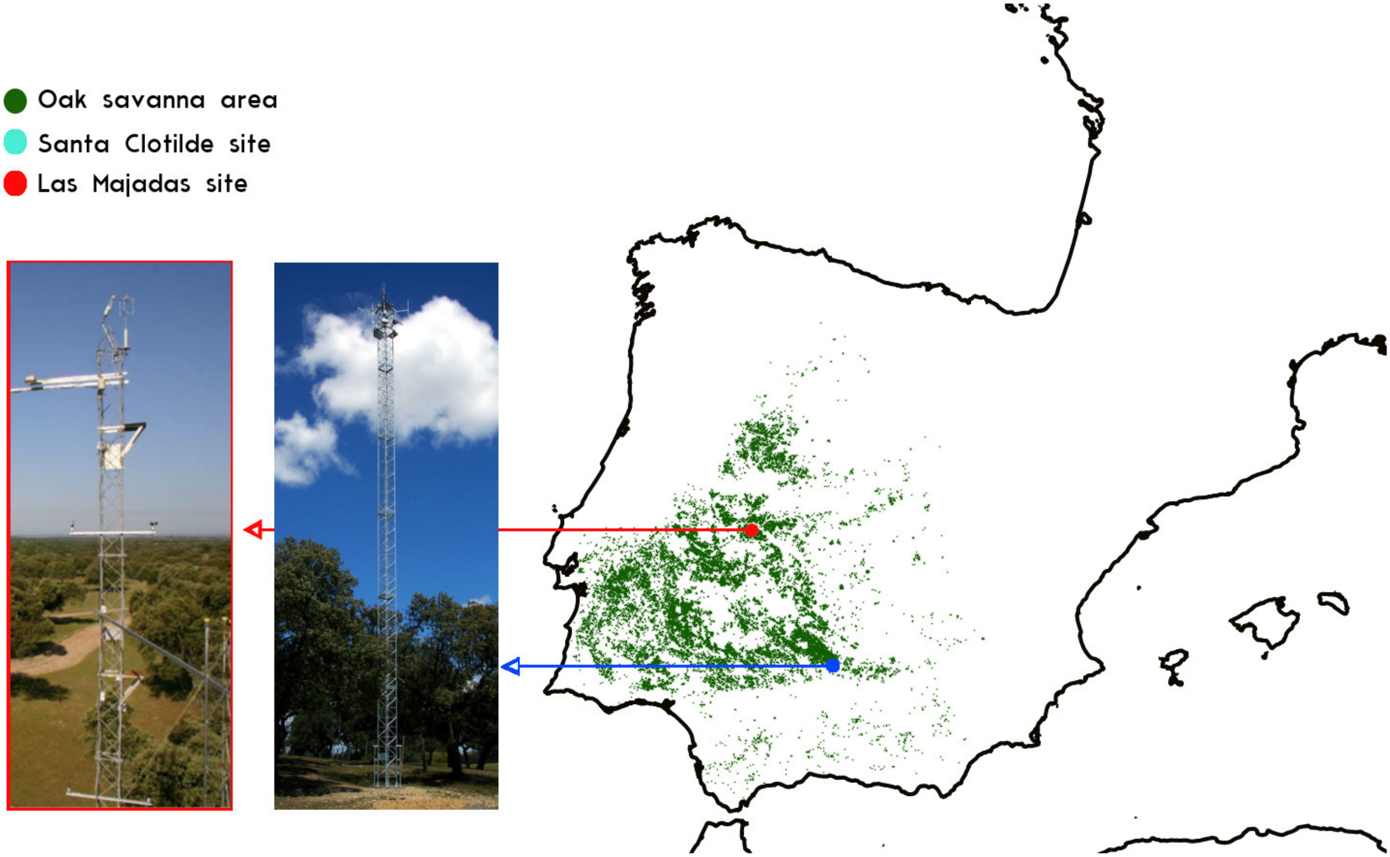

Figure 1

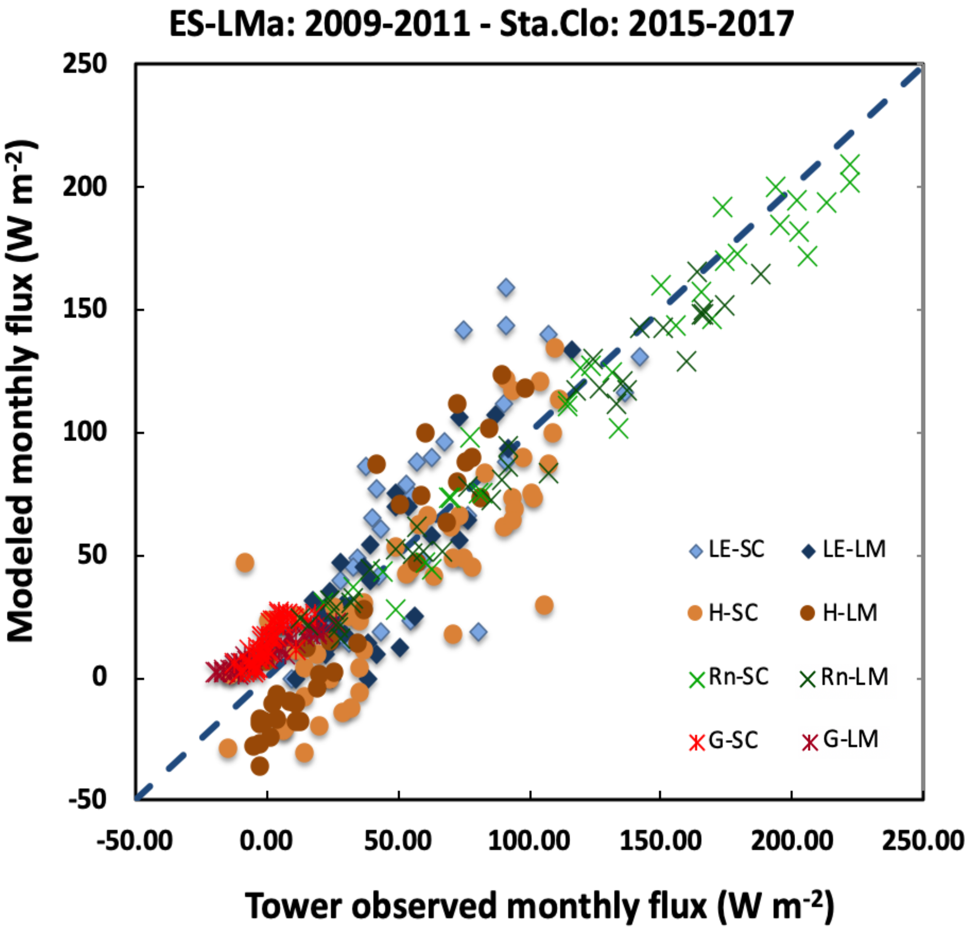
ES-LMa: 2009-2011 - Sta.Clo: 2015-2017
Modeled monthly flux (W m-2)
250
200
150
100
50
0
-50
-50.00
0.00
50.00
100.00
150.00
200.00
250.00
Tower observed monthly flux (W m-2)
LE-SC
LE-LM
H-SC
H-LM
Rn-SC
Rn-LM
G-SC
G-LM

Figure 2

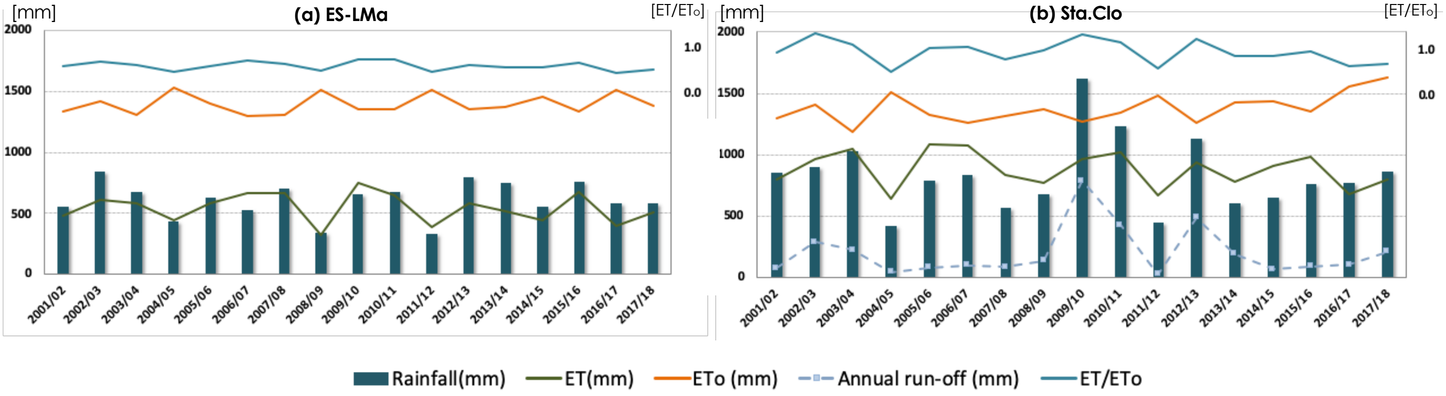
[mm]
(a) ES-LMa
[ET/ETo]
2000
1500
1000
500
0
1.0
0.0
2001/02
2002/03
2003/04
2004/05
2005/06
2006/07
2007/08
2008/09
2009/10
2010/11
2011/12
2012/13
2013/14
2014/15
2015/16
2016/17
2017/18
[mm]
(b) Sta.Clo
[ET/ETo]
2000
1500
1000
500
0
1.0
0.0
2001/02
2002/03
2003/04
2004/05
2005/06
2006/07
2007/08
2008/09
2009/10
2010/11
2011/12
2012/13
2013/14
2014/15
2015/16
2016/17
2017/18
Rainfall(mm)
ET(mm)
ETo (mm)
Annual run-off (mm)
ET/ETo

Figure 3

ET/ETo-μ
σ
2
1
0
-1
-2
2001/02
2002/03
2003/04
2004/05
2005/06
2006/07
2007/08
2008/09
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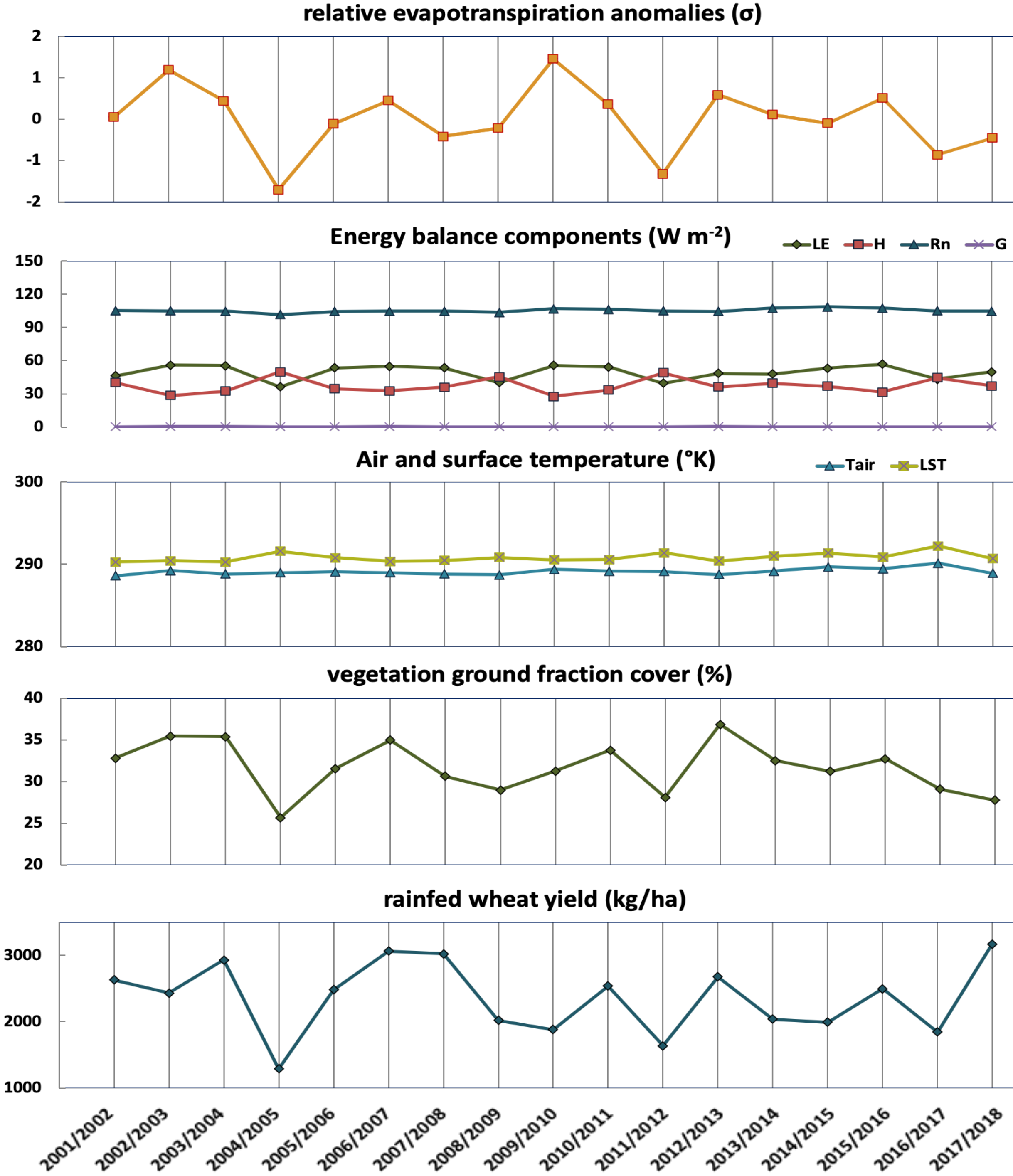
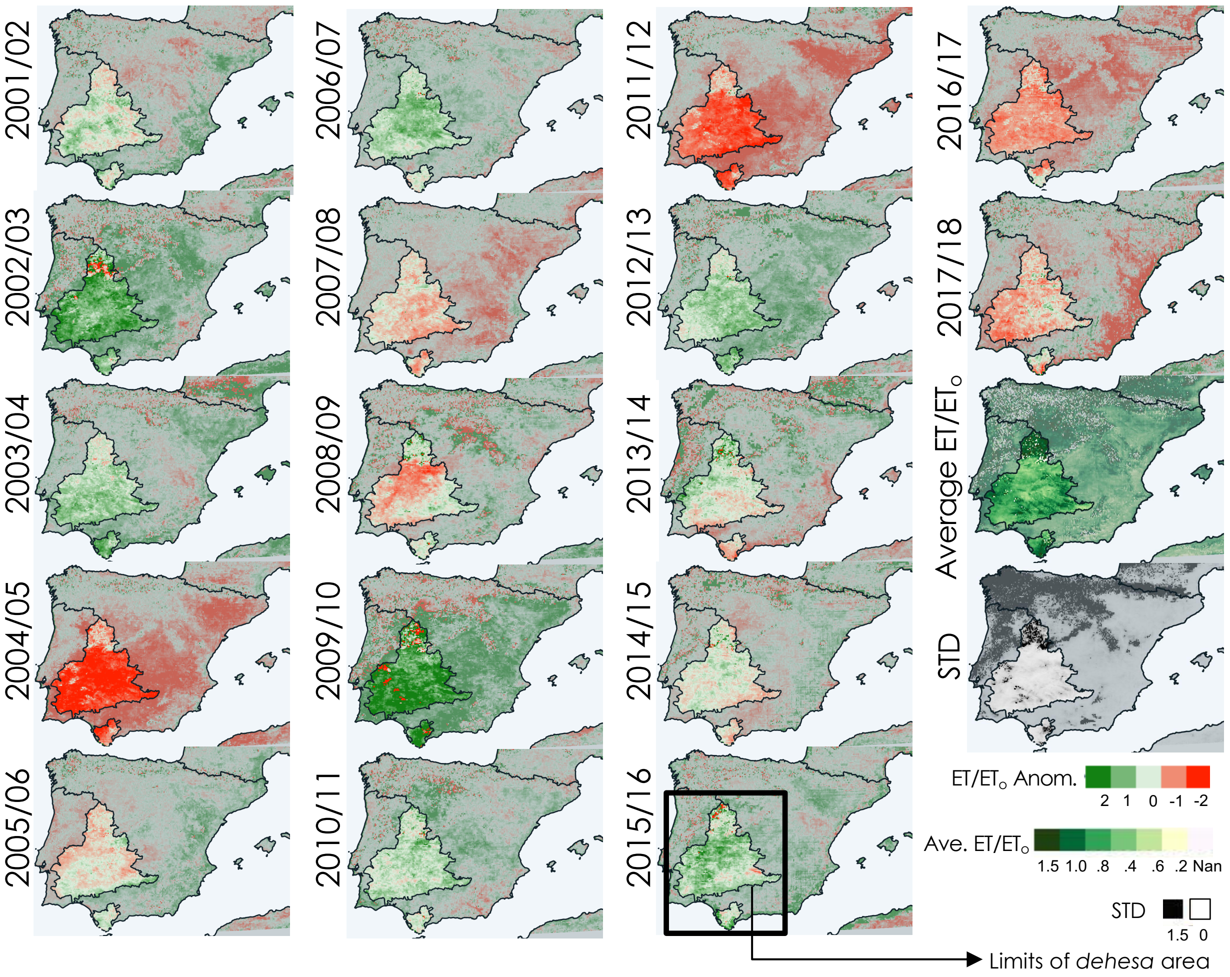
2013/14
2014/15
2015/16
2016/17
2017/18
Sta.Clo
ES-LMa

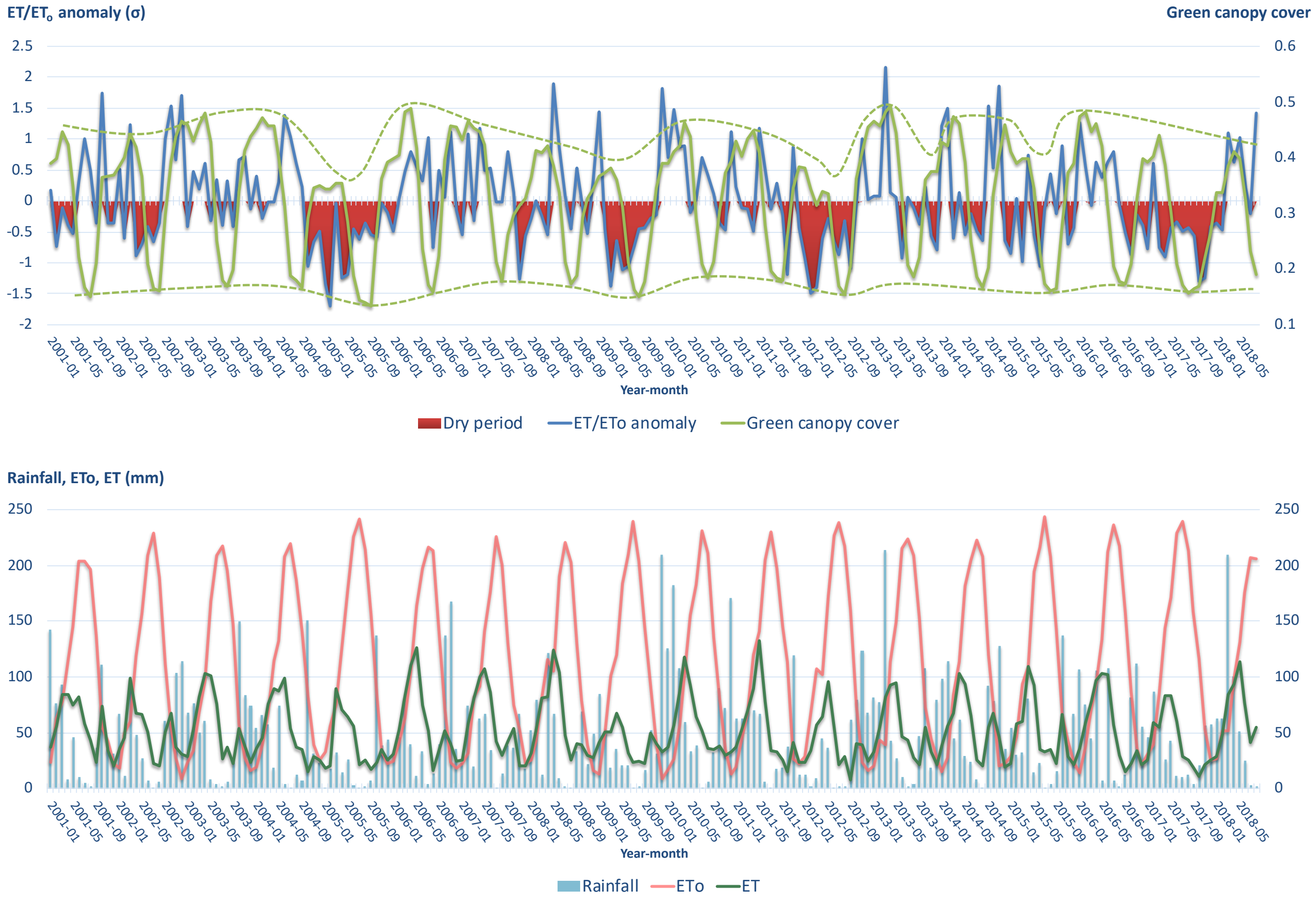
Figure 4



modified Figure 5



modified Figure 6


ET/ET$_o$ anomaly (σ)
Green canopy cover
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.6
0.5
0.4
0.3
0.2
0.1
Year-month
Dry period
ET/ETo anomaly
Green canopy cover
Rainfall, ETo, ET (mm)
250
200
150
100
50
0
Year-month
Rainfall
ETo
ET
2001-01
2001-05
2001-09
2002-01
2002-05
2002-09
2003-01
2003-05
2003-09
2004-01
2004-05
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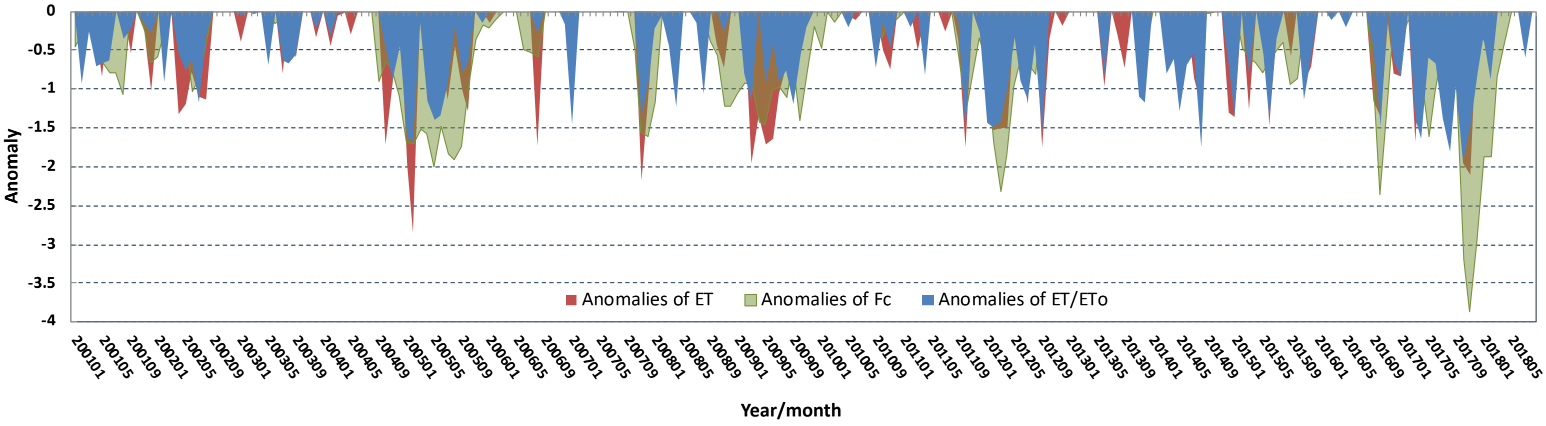
2017-05
2017-09
2018-01
2018-05

Figure 7


0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
Anomaly
Anomalies of ET
Anomalies of Fc
Anomalies of ET/ETo
200101
200105
200109
200201
200205
200209
200301
200305
200309
200401
200405
200409
200501
200505
200509
200601
200605
200609
200701
200705
200709
200801
200805
200809
200901
200905
200909
201001
201005
201009
201101
201105
201109
201201
201205
201209
201301
201305
201309
201401
201405
201409
201501
201505
201509
201601
201605
201609
201701
201705
201709
201801
201805
Year/month

new Figure 8