Reply to Referee #1

We would like to thank referee #1 for the detailed review of our manuscript and the suggestions that will help to improve our manuscript. In the following, we will answer each of the referee's comments.

This short paper attempts to describe the impacts of land degradation in semiarid ecosystems on carbon fluxes on the basis of the differences observed between two eddy covariance flux sites in SE Spain. The authors clearly demonstrate that most of the expected meteorological controls over C flux are equivalent between sites, but the carbon fluxes are striking different, varying by a couple of orders of magnitude. As they highlight, this difference in observed net carbon flux is a result of contrasting fluxes of carbon from "subterranean ventilation". As the authors have addressed in other publications, this large carbon efflux cannot be accounted for due to in-situ concurrent biological activity – and this greatly complicates interpretation of contrasting results between the sites, and thus the assessment of the impacts of land degradation.

Unfortunately, the authors do not address this challenge very effectively, and in its current form there is little support for any conclusion about the impacts of land degradation on carbon fluxes. It maybe that the nature of the sites makes it impossible to carry out such a comparison convincingly, but addressing a number of areas is required before this can be determined.

General comments

1. First, the nature of the disturbance and extent to degradation needs to be described in more detail. The similarities between the sites are described in detail, but the crucial differences need more full description than Table 1, and more importantly, the biological implications of these differences (detailed hypotheses) need to be articulated.

We agree with the reviewer. Therefore, the following paragraph will be added to the revised manuscript in page 3 line 20:

"Some land degradation processes are evident when we compare the "natural" site with the "degraded" site. This land degradation processes can directly affect abiotic and/or biotic factors, which in turn influence the biological

and/or non-biological processes that compose the net ecosystem CO_2 *exchange. Firstly, vegetation cover is almost 3 times higher in Balsa Blanca (BB), the "natural" site; this implies for the degraded site higher thermal and radiative stress in the soil, especially during the drought period (Rey et al., 2017). The overall hypothesized effects of this degradation driver on biological processes are a direct reduction in plant productivity and respiration, and an indirect decrease in heterotrophic respiration. Secondly, the higher cover of bare soil and outcrops in Amoladeras (AMO), the "degraded" site, may increase the soil-atmosphere interconnectivity, which indirectly can enhance advective* CO_2 *release through subterranean ventilation. Thirdly, the reduced soil fertility and depth may provoke changes in microbial communities (Evans and Wallenstein, 2014) due to stronger nutrient and water limitations. Consequently, a direct decrease in heterotrophic respiration and plant productivity and respiration is expected."*

2. Second, these hypotheses need to detail biological controls and the non-biological controls over C fluxes at these two sites, and the fluxes need to be interpreted in that light. In particular, it is differences in productivity that would be key to understanding this. Although it will be difficult given the atypical conditions of a large non-concurrent biological carbon efflux, NEE should be partitioned, and GPP between the sites compared. In addition, there should be a more detailed comparison of the ET fluxes, which in these ecosystems seem to be providing a more comparable indication of ecosystem function. And taken together, it would be interesting to assess inter-site differences in water use efficiency.

According to the referee's suggestion, we have partitioned the net CO_2 *fluxes* (F_c) *in order to assess the potential direct influence of land degradation on the gross primary production (GPP) and ecosystem respiration* (R_{eco}) *components. Given the extreme* CO_2 *release detected due to subterranean ventilation, two steps have been performed at each site.*

Firstly, we have modelled the ventilative CO_2 *efflux by adapting the approach proposed by (Pérez-Priego et al., 2013) with the results of previous studies performed in both sites (López-Ballesteros et al., 2016; 2017). Essentially, we aimed to isolate those moments when subterranean ventilation* (V_n) *dominates the* F_c *and biological fluxes are negligible. These moments correspond to daytime hours during the extremely dry periods. Data were selected using the following conditions:*

- *(i)* *Net radiation > 10 W* m^{-2}
- *(ii)* *8 < Daily averaged bowen ratio < 10*
- *(iii)* *Daily soil water content (in bare soil) < 10th percentile (Amoladeras) and < 20th percentile (Balsa Blanca)*

A less restrictive threshold was used in Balsa Blanca in order to get enough data to build the V_n *model, since long-term data gaps occurred in Balsa Blanca during the summer seasons of 2012, 2014 and 2015. Afterwards, in order to build the linear model of* V_n*, these selected* F_c *data (maximum quality; QC flag=0) were related to the friction velocity (*u_**). The model results for both sites are shown below:*

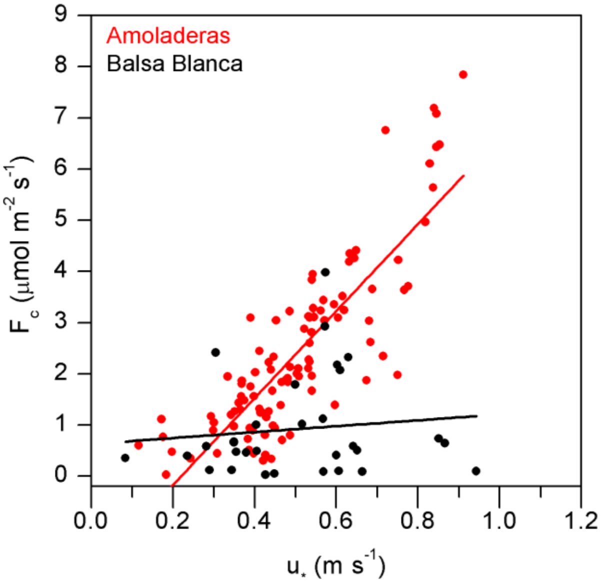


Figure S1: Half-hourly net CO_2 *fluxes of maximum quality (QC flag=0) versus friction velocity (*u_**) corresponding to daytime hours during the extremely dry periods when subterranean ventilation dominates the net* CO_2 *flux. Red and black dots represent Amoladeras and Balsa Blanca, respectively.*

Model parameters	***Amoladeras***	***Balsa Blanca***
Intercept ± error (p-value)	*-1.876 ± 0.291 (4e-09)*	*0.628 ± 0.508 (0.226)*
Slope ± error (p-value)	*8.500 ± 0.549 (<2e-16)*	*0.578 ± 0.944 (0.545)*
R^2	*0.706 (<2.2e-16)*	*0.013 (0.5451)*
n	*102*	*31*

Table 3: Linear regression results between half-hourly net CO_2 *fluxes of maximum quality (QC flag=0) and friction velocity (*u_**) used to model subterranean ventilation.*

As the table above shows, the V_n model is uniquely valid for Amoladeras.

Therefore, we only applied the V_n model to Amoladeras data, concretely, during those periods were ventilation occurs according to previous research (López-Ballesteros et al., 2017):

- *(i)* *Net radiation > 10 W m^{-2}*
- *(ii)* *Daily averaged bowen ratio > 4*
- *(iii)* *Daily soil water content (in bare soil) < 0.01 m^3 m^{-3}*
- *(iv)* σ_{swc} *(daily variance of soil water content in bare soil)< 5e-6 (m^3 m^{-3})^2*

We use those moments with very low σ_{swc} in order to discern R_{eco} increases caused by rain pulses (Birch effect) from V_n fluxes during the dry season.

Then, the modelled ventilative fluxes were substracted from the measured F_c to obtain the F_c corresponding only to biological processes (i.e. biological F_c; see Figure below).

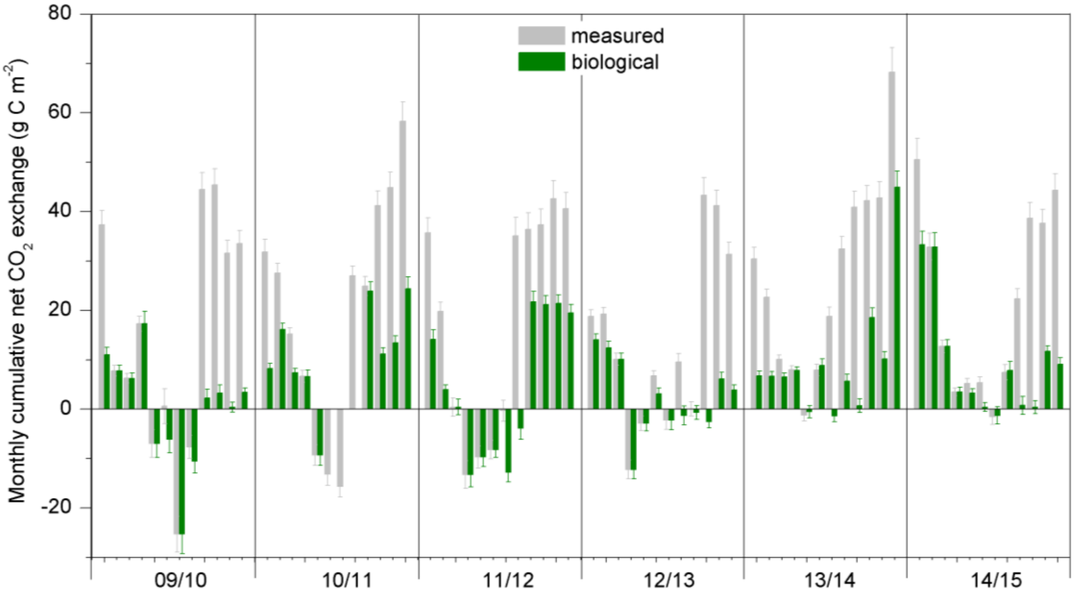


Figure S1: Cumulative measured and biological (after applying the ventilation model) net CO_2 exchange for every month of the study period (5 hydrological years; 2009-2015) in Amoladeras.

Secondly, the partitioning approach proposed by Lasslop et al. (2010) was applied to the biological F_c for both sites in order to obtain GPP and R_{eco} fluxes. We chose this approach given the determinant influence of hydric stress, in this case *atmospheric drought (assessed via VPD), on the physiology of Machrocloa tenacissima, the dominant plant species of the studied semiarid ecosystems (Pugnaire et al., 1996; López-Ballesteros et al. 2016).*

This information would be added to a new section within the manuscript, concretely the subsection "2.3. Flux partitioning to estimate GPP and R_{eco}" within the Material and Methods section.

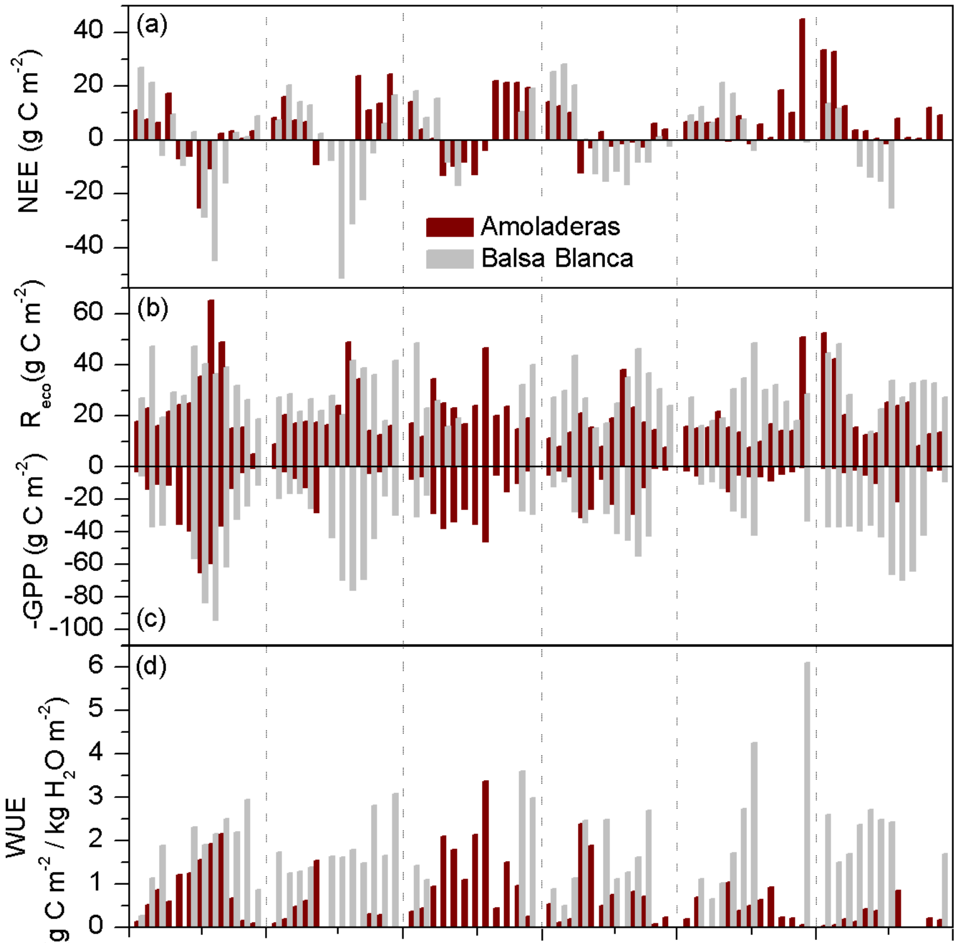


Figure 7: Monthly cumulative fluxes of (a) biological net ecosystem CO_2 exchange, (b) ecosystem respiration (R_{eco}), (c) negative gross primary production and (d) water use efficiency over the six hydrological years of study (2009-2015) for Amoladeras (dark red) and Balsa Blanca (grey). Lacking bars correspond to long-term data losses.

Finally, the results of the “biological” annual carbon balance are in accordance with the hypotheses, since annual C emission was always measured at the “degraded” site, whereas the “natural” site acted as a neutral and mild C sink. On average, Amoladeras emitted 32 g C m^{-2} more than Balsa Blanca.

Year	*Amoladeras*	*Balsa Blanca*
2009/2010	*3+-7*	*-32+-10*
2012/2013	*28+-5*	*0+-8*

We could not compare the annual C balance of 2010/2011 between sites due to a long-term data gap in the u_* time series in Amoladeras during the spring months (February-April).

During autumn, monthly biological net CO_2 fluxes were, on average, ~4 times higher at the “natural” site, excepting the last study year, when the net CO_2 emission at the “degraded” site was 21 times greater than at the “natural” site. However, during winter and spring months, net CO_2 uptake was generally higher at the “natural” site (Fig. 5a).

On average, during the six years of study, GPP, R_{eco} and WUE were nine, twice and ten times higher, respectively, at the “natural” site compared to the “degraded” site. Firstly, GPP was always higher at the “natural” site compared to the “degraded” site (Fig. 7c). Major differences occurred in autumn 2014/2015, when monthly cumulative GPP at the “natural” site was 32 times higher on average. Similarly, R_{eco} was generally higher, up to 786% (October 2014), at the “natural” site. However, respiratory fluxes were occasionally greater at the “degraded” site, from 2% to 31% higher, during spring and winter months of all studied years excepting 2013/2014 (Fig .7b). Maximum inter-site differences in GPP and R_{eco} were found in winter and autumn 2014/2015, following the driest year, when monthly GPP was, on average, ~30 times higher at the “natural” site compared with the “degraded” site. Similarly, monthly R_{eco} was ~5 times greater at the “natural” site. Inter-site differences in partitioned fluxes could not be assessed during spring months due to the lack of data from the “natural site”. Secondly, Water Use Efficiency (WUE) was lower at “the “degraded” site showed during the whole study period, when maximum and minimum differences coincided with the highest and lowest differences in GPP between sites. On average, monthly WUE was 6 and 1.5 times higher in the “natural” site during winter and spring. Major inter-site differences were found in autumn and winter 2014/2015 (Fig. 7d).

This information would be added to a new section within the manuscript, the subsection "3.4. Biological Net Ecosystem Exchange, Gross Primary Production, Ecosystem Respiration and Water Use Efficiency" within the Results section. Accordingly, these results would be discussed and related to the study hypotheses in the Discussion section.

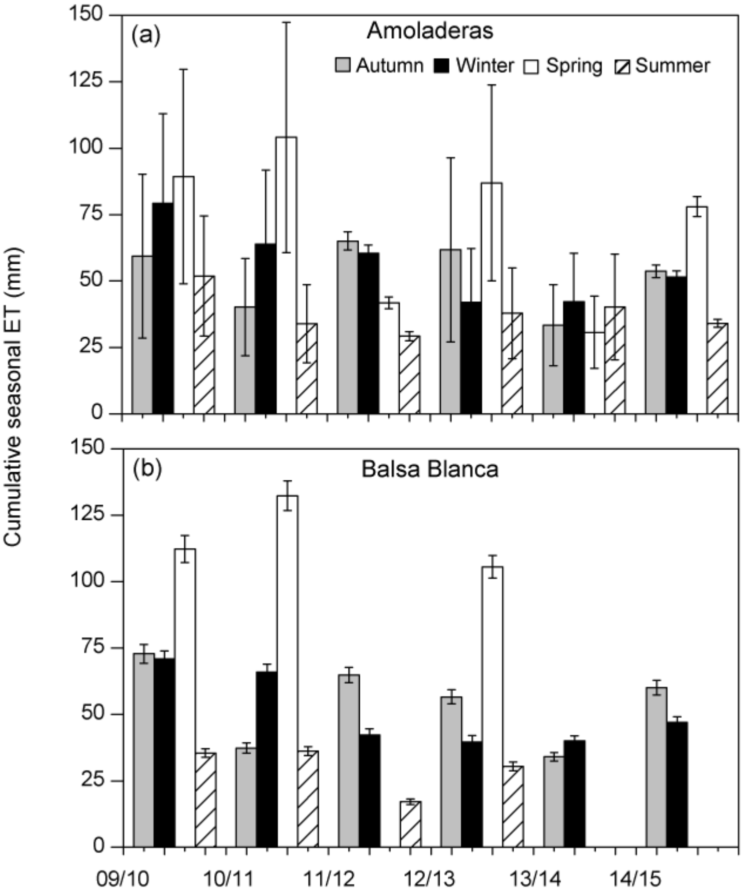


Figure 5: Cumulative seasonal evapotranspiration fluxes (ET) over the study period in both experimental sites. In case of Balsa Blanca, lacking bars correspond to long-term data losses (>50% data). Error bars denote uncertainty derived from the gap-filling procedure.

Apart from that, ET results showed ~30% higher ET at the "natural" site compared to the "degraded" site during spring. Major inter-site differences in autumn occurred in the first and last year of study, when ET was 23% and 12% higher at BB, respectively. In this regard, we think that the "natural" site shows more capacity to maintain water availability during the growing season, however, the *lack of data complicates the interpretation. The higher uncertainty of ET data in Amoladeras is due to a higher fraction of short-term data gaps compared to Balsa Blanca, on average annual fraction of data losses is 27% higher in Amoladeras.*

This information would be added to the subsection 3.3., which would be renamed as "Seasonal and diurnal net CO_2 *and water vapor exchanges" within the Results section. Accordingly, these results will be discussed in the Discussion section.*

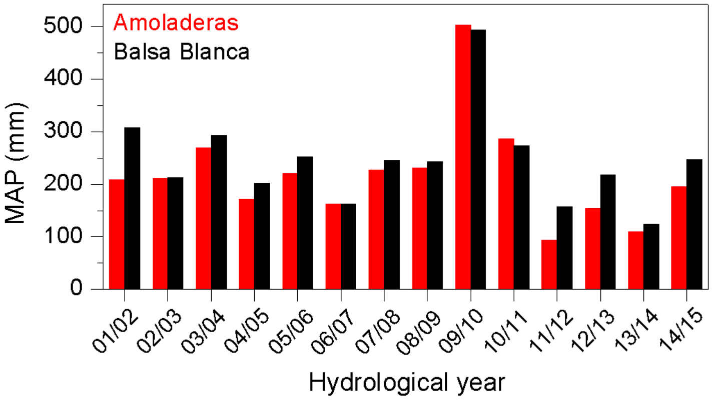
3. Third, the EVI time series as an indicator of productivity requires a closer examination. Given the differences in vegetation cover between the sites (Table 1), it is the similarity in EVI values, rather than the differences (except in the final year), between the two sites that seems most striking. This would suggest that productivity between the sites is not very different, and EVI based GPP estimates would be similar. Does observed tower GPP support this?

As stated before, we have found that GPP was always higher at the "natural" site compared to the "degraded" site. Thus, there is a discrepancy between GPP estimates and EVI values. We think that this is due to the different spatial scales defining every measurement. MODIS pixels have an area of ~6.25 ha while the eddy covariance footprint corresponds to a smaller area of ~1ha. Therefore, there is an EVI uncertainty that stems from the influence of other surface elements apart from vegetation, such as bare soil or outcrops within the pixel, which is our case. In fact, previous studies confirm the discrepancy between MODIS- and EC-derived GPP estimates, especially on sparse vegetation areas with low productivity (Gilabert et al., 2015).

This information would be added to the fifth paragraph of the Discussion section of the revised manuscript.

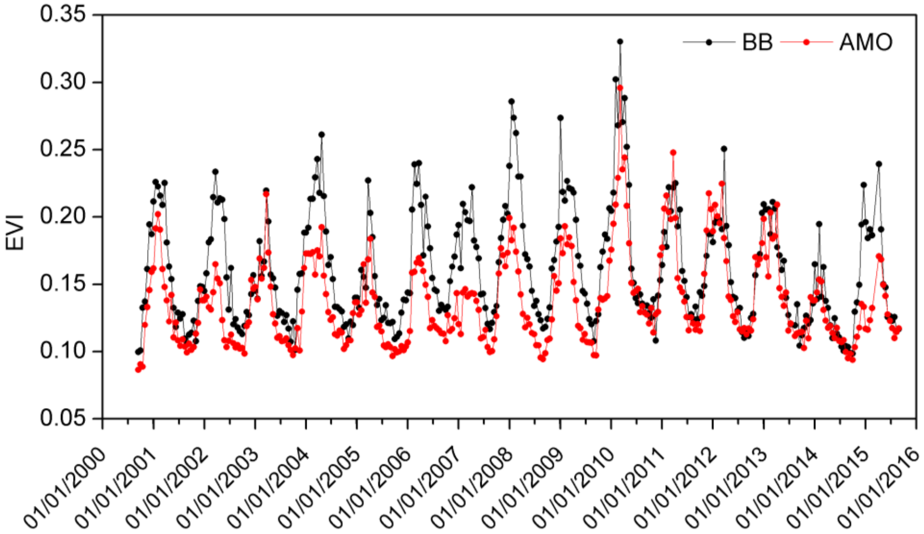
4. Fourth, the downward trend in maximum annual EVI is interesting, and could be investigated more, and potentially over a longer time period. Is it significantly related to a trend in precipitation, and a trend in productivity from the towers? The contrasting response between the sites in the final year of the record is striking, is it reflected in the tower flux record also – it seems the record is complete over the winter period at least?

The period we are studying is too short to assess trends. In addition, precipitation in this region is quite variable and as said before, the direct comparison between EVI and GPP estimates from EC measurements can lead to biased conclusions. Apart *from that, if we look to a wider time window, by using longer time series of EVI and precipitation, we can realize that the precipitation in 2009/2010 was extremely high compared with the annual precipitation of the experimental sites, which equates to 220 mm (Table 1). Thus, we believe that instead of a decreasing trend what we see is a pulse response following the wettest year, as can be seen in the figures below. In fact, inter-site differences in EVI are greater before the study period, from 2000 to 2009, compared to 2009-2014. During the last year of the study period, this difference became similar to the pattern observed before the wettest year.*



Notice that precipitation data shown in the figure above have not been measured in the experimental sites but quite near them since the EC stations were installed in 2006 (Balsa Blanca) and 2007 (Amoladeras). Concretely, the agro-climatic stations, "Almería" and "Níjar", where precipitation was measured, are 13.55 km and 11.22 km from Amoladeras and Balsa Blanca, respectively.

Source:
https://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController?action=Init



5. Fifth, given that soil CO_2 concentration is measured at two depths, is it possible to estimate soil CO_2 flux? This could be used to partition the concurrent biological CO_2 signal, versus non-biological, and potentially the impacts of degradation on these two different processes.

The estimation of soil CO_2 efflux by using the gradient method (Sánchez-Cañete and Kowalski, 2014) assumes that the release of CO_2 from soil is performed by diffusion exclusively. However, as demonstrated in previous studies, advection (non-diffusive transport) can play an important role in the soil-atmosphere gaseous exchange (Kowalski et al., 2008; Sanchez-Cañete et al., 2011; Sánchez-Cañete et al., 2016; López-Ballesteros et al., 2017; Serrano-Ortiz et al., 2009; Subke et al., 2003; Risk et al., 2013; Roland et al., 2015). Further isotopic analyses are necessary to assess the role of biological vs non-biological CO_2 production processes in soil CO_2 efflux as well as to determine the transport processes driving the soil-atmosphere net CO_2 exchange. Unfortunately, we do not have these results, although we plan to work on it in the near future. Additionally, through the application of the ventilation model (previously explained), we have discriminated between the biological and non-biological net ecosystem CO_2 exchange in Amoladeras.

Overall, a considerable amount of additional analysis is required to separate out the signal from biological and non-biological controls over carbon fluxes from these two sites. It is only then when the flux can be interpreted in terms of vegetation productivity that the impacts of degradation can be assessed in a way that provides insight into processes that are more broadly applicable across semiarid ecosystems.

We believe that the empirical ventilation model that we have added (see above) should satisfy the referee in this regard.

Specific comments

There are very few grammatical and spelling errors, a few very minor points:

P2 L19 – “concretely” is a strange word choice here and elsewhere – “definitively” is better in some cases, or it can just be removed.

We agree and we have removed “concretely” from the sentence.

P7 L31 - “punctual’ is a strange word choice here – not sure what you are trying to convey.

We agree about “punctual” should be removed from the sentence. What we wanted to say is that EVI data is discrete as oppose to fluxes but this information is already explained in the material and methods section.

P7 L32 – Daily time series are hard to decipher in Figure 5. It is always a challenge to convey this information. Maybe using a solid black, and ensuring the graphic is a full-page width would help.

We believe that this picture carries much information that has to be shown and complements other figures (Fig. 4, 5 and 7) where flux data are aggregated. After trying several graphical options, we decided to use dashed lines because solid black lines (Balsa Blanca data) mask the red lines (Amoladeras data). We have increased the width of the figure and thickened the black lines.

P9 L3 – I believe it would be normal to correct pressure to sea-level equivalents before making comparisons such as these.

We agree so we have corrected pressure to sea level equivalents using the hypsometric equation and afterwards we have computed the Wilcoxon test for the different analysis periods. Results show a smaller difference between sites in corrected pressure compared to uncorrected values. These results (table below) would substitute previous ones (Tables 4, S1, S2 and S3) in the revised version of the manuscript.

Period	**Diff**	**$Diff_{st}$**	**p-value**	**n**
All periods	*2.3226*	*0.3737*	*0*	*166336*
May-September	*2.2120*	*0.5828*	*0*	*71188*
May-September Daytime	*2.1101*	*0.5602*	*0*	*34280*

Evans, S. E., and Wallenstein, M. D.: Climate change alters ecological strategies of soil bacteria, Ecology Letters, 17, 155-164, 10.1111/ele.12206, 2014.

Gilabert, M. A., Moreno, A., Maselli, F., Martínez, B., Chiesi, M., Sánchez-Ruiz, S., García-Haro, F. J., Pérez-Hoyos, A., Campos-Taberner, M., Pérez-Priego, O., Serrano-Ortiz, P., and Carrara, A.: Daily GPP estimates in Mediterranean ecosystems by combining remote sensing and meteorological data, ISPRS Journal of Photogrammetry and Remote Sensing, 102, 184-197, https://doi.org/10.1016/j.isprsjprs.2015.01.017, 2015.

Kowalski, A. S., Serrano-Ortiz, P., Janssens, I. A., Sánchez-Moral, S., Cuezva, S., Domingo, F., Were, A., and Alados-Arboledas, L.: Can flux tower research neglect geochemical CO2 exchange?, Agricultural and Forest Meteorology, 148, 1045-1054, 2008.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneth, A., Barr, A., Stoy, P., and Wohlfahrt, G.: Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation, Global Change Biology, 16, 187-208, 10.1111/j.1365-2486.2009.02041.x, 2010.

López-Ballesteros, A., Serrano-Ortiz, P., Kowalski, A. S., Sánchez-Cañete, E. P., Scott, R. L., and Domingo, F.: Subterranean ventilation of allochthonous CO2 governs net CO2 exchange in a semiarid Mediterranean grassland, Agricultural and Forest Meteorology, 234–235, 115-126, http://dx.doi.org/10.1016/j.agrformet.2016.12.021, 2017.

Pérez-Priego, O., Serrano-Ortiz, P., Sánchez-Cañete, E. P., Domingo, F., and Kowalski, A. S.: Isolating the effect of subterranean ventilation on CO2 emissions from drylands to the atmosphere, Agricultural and Forest Meteorology, 180, 194-202, 2013.

Pugnaire, F. I., Haase, P., Incoll, L. D., and Clark, S. C.: Response of the tussock grass Stipa tenacissima to watering in a semi-arid environment, Functional Ecology, 10, 265-274, 1996.

Rey, A., Oyonarte, C., Morán-López, T., Raimundo, J., and Pegoraro, E.: Changes in soil moisture predict soil carbon losses upon rewetting in a perennial semiarid steppe in SE Spain, Geoderma, 287, 135-146, http://dx.doi.org/10.1016/j.geoderma.2016.06.025, 2017.

Risk, D., Lee, C. K., MacIntyre, C., and Cary, S. C.: First year-round record of Antarctic Dry Valley soil CO2 flux, Soil Biology and Biochemistry, 66, 193-196, http://dx.doi.org/10.1016/j.soilbio.2013.07.006, 2013.

Roland, M., Vicca, S., Bahn, M., Ladreiter-Knauss, T., Schmitt, M., and Janssens, I. A.: Importance of nondiffusive transport for soil CO2 efflux in a temperate mountain grassland, Journal of Geophysical Research: Biogeosciences, 120, 502-512, 10.1002/2014jg002788, 2015.

Sanchez-Cañete, E. P., Serrano-Ortiz, P., Kowalski, A. S., Oyonarte, C., and Domingo, F.: Subterranean CO2 ventilation and its role in the net ecosystem carbon balance of a karstic shrubland, Geophysical Research Letters, 38, 2011.

Sánchez-Cañete, E. P., and Kowalski, A. S.: Comment on “Using the gradient method to determine soil gas flux: A review” by M. Maier and H. Schack-Kirchner, Agricultural and Forest Meteorology, 197, 254-255, http://dx.doi.org/10.1016/j.agrformet.2014.07.002, 2014.

Sánchez-Cañete, E. P., Oyonarte, C., Serrano-Ortiz, P., Curiel Yuste, J., Pérez-Priego, O., Domingo, F., and Kowalski, A. S.: Winds induce CO2 exchange with the atmosphere and vadose zone transport in a karstic ecosystem, Journal of Geophysical Research: Biogeosciences, n/a-n/a, 10.1002/2016jg003500, 2016.

Serrano-Ortiz, P., Domingo, F., Cazorla, A., Were, A., Cuezva, S., Villagarcía, L., Alados-Arboledas, L., and Kowalski, A. S.: Interannual CO2 exchange of a sparse Mediterranean shrubland on a carbonaceous substrate, Journal of Geophysical Research G: Biogeosciences, 114, 2009.

Subke, J.-A., Reichstein, M., and Tenhunen, J. D.: Explaining temporal variation in soil CO2 efflux in a mature spruce forest in Southern Germany, Soil Biology and Biochemistry, 35, 1467-1483, http://dx.doi.org/10.1016/S0038-0717(03)00241-4, 2003.