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Interactive comment on "Large but decreasing effect of ozone on the European carbon sink" *by* Rebecca J. Oliver et al.

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Response to RC1:

We would like to thank the reviewer for their time taken to read and comment on this manuscript. The comments have been very helpful to improve the manuscript. We hope we have addressed the comments to the full satisfaction of the reviewer. We attach the revised manuscript with track changes so it can be seen what has been changed and where.

This paper investigated the interaction between CO2 and O3, the two greenhouse gases that directly affect plant photosynthesis, and indirectly gs. The goal of the paper is to quantify the impact of tropospheric O3, and its interaction with CO2, on gross

primary productivity and land carbon storage across Europe from 1901 to 2050 using the JULES land-surface model. In principle, the analysis is highly topical and needed.

RC1) Throughout the abstract, it should be more quantitative in nature. For example, line 37-38, by how much does the tropospheric O3 suppress terrestrial carbon uptake?

AC: We have modified the abstract to make it more quantitative (lines 37 to 47).

RC2)Line 40-41, How much of the combined effects of elevated future CO2 (acting to reduce stomatal opening) and reductions in O3 concentrations resulted in reduced O3 damage? Moreover, elevated future CO2 will lead to climate warming simultaneously, so how do the authors remove the response of GPP and land carbon uptake to climate warming due to the increased CO2 concentration? Warming will also increase evaporation (evapotranspiration) and reduce soil water availability, is this also considered?

AC: We have added a sentence to the abstract to show that the alleviation of O3 damage by CO2 induced stomatal closure was around 1 to 2% for the low and high plant O3 sensitivities respectively (for both GPP and land C, line 42). This is discussed in more detail in the original manuscript in the Results section 3.4 pg. 18 on lines 609 to 614 and in Table S6.

This study uses a fixed climate. We cycle over the climate from 1901 to 1920 so we maintain natural climate variability, but we do not have climate change. This allows us to focus on the direct effects of changing atmospheric CO2 and O3 concentrations, and their complex interaction, on plant physiology through the twentieth century and into the future. We acknowledge the use of a 'fixed' pre-industrial climate omits the additional factor of the interaction between climate change and gs which will affect the rate of O3 uptake and therefore O3 concentrations. Nevertheless, these simulations are an important tool to understand the direct impacts of O3 at the land surface. This work demonstrates the sensitivity of GPP and the land carbon sink to tropospheric O3, highlighting that it is an important predictor of future GPP. We do state in the original manuscript that we use a fixed climate (methods section 2.4.1 line 373), but we realise that we do not make it clear enough early on in the manuscript that we use a fixed climate, so we have amended this in the introduction (pg.6 , lines 214 to 223). We also add a paragraph to our discussion about potential impacts on our results (section 4.3, pg. 26, lines 808 to 816).

RC3)Line 43, how large are the regional variations in temperate boreal regions? Overall, some specific problems should be described in Introduction. For the O3 effect on the land C sink, what have we learned from the previous studies? What bioregions, and with what methods, have been studied?

AC: We have added a new paragraph to the introduction to discuss the findings from previous studies from different regions (pg. 4, lines 134 to 157). Also, we have quantified the regional variations in the abstract (line 44), and in the original manuscript we discuss these spatial variations in greater detail in the results section.

RC4)Line 81-83, The authors mentioned few studies have considered the simultaneous effects of exposure to both O3 and CO2, so what have learned from these previous studies? Please specify previous findings.

AC: See response to comment above. We have added a new paragraph to the introduction to discuss previous studies, both field and model-based, and what has been shown from these studies (pg. 4, lines 134 to 157).

RC5)Line 86-99, Please describe the O3 concentration for historical and current level in quantity. How does the O3 change over the last decades?

AC: We have added more information about the change in O3 concentrations from historical to present day (pg.3, lines 88 to 98).

RC6)Line 103-104, High levels of O3 are reducing the land carbon sink. How many carbon loss was led to by O3 at regional and global scale based on previous studies?

AC: We have added a paragraph to the introduction to discuss the findings of previous studies (pg. 4, lines 134 to 157).

RC7)Line 121-122, are you also going to study the effects of high temperature and drought?

AC: This links to an earlier comment – in this study we have used a fixed pre-industrial climate. We cycle over the climate from 1901 to 1920 so we maintain natural climate variability, but we do not have climate change. This allows us to focus on the direct effects of changing atmospheric CO2 and O3 concentrations, and their complex interaction, on plant physiology through the twentieth century and into the future. We realise that we do not make it clear enough early on in the manuscript that we use a fixed climate, so we have amended this in the introduction (pg.6 , lines 214 to 223). We also add a paragraph to our discussion about potential impacts on our results (section 4.3, pg. 26, lines 808 to 816).

RC8)Please explain the CUO1 in Figure S2 caption. As shown in Table S1, the g1 parameter in NT (Needle leaf tree) is similar to that of shrub. Does it mean plant water use efficiency in NT and SH are same?

AC: We have clarified this by adding the following to the Figure S2 caption: “The x axis is cumulative uptake of O3 (CUO) above the critical O3 threshold (FO3crit).” The parameter values for g1 were derived from the extensive database of Lin et al., (2015). The parameter g1 is a measure of water-use efficiency. In the model, the plant water-use efficiencies of NT and SH would be similar but not identical since WUE is the ratio of carbon gain to water loss and the two PFTs have different photosynthetic rates owing to different parameter values.

RC9)Figure1, could you provide some O3 concentration data from observations?

AC: This links to an earlier comment #5. Comparison of these long-term O3 trends with observations is difficult for many reasons, not least lack of reliable data before recent decades, and limited representativity and inconsistencies in data from recent years (Logan et al., 2012;Parrish et al., 2012). For example, ozone levels at the start of the 20th century are estimated to be around 10 ppb for the site Montsouris Observatory near Paris, data for Arkona on the Baltic coast increased from ca. 15 ppb in the 1950s to 20-27 ppb by the early 1980s, and the Irish coast site Mace Head shows around 40 ppb by the year 2000 (Logan et al., 2012, Parrish et al., 2012, and refs within). Trends vary from site to site though, even on a decadal basis (Logan et al., 2012;Simpson et al., 2014), depending, for example, on local/regional trends in precursor (especially NOx) emissions, elevation, and exposure to long-range transport. As a result of this spatial variation in O3 concentrations across Europe, comparison of the EMEP O3 forcing in Fig. 1 (plotted as a mean across regions) with individual sites would potentially be misleading.

RC10)Line 342-345, what is the uncertainty (or SD) for these percentage number? It may be better if the authors mentioned how these number are calculated in methods.

AC: These numbers were re-calculated to get the standard deviation. Previously the annual mean for each simulation was calculated, and this used to calculate the percentage difference. To get the standard deviation the daily means were calculated and the percentage difference was calculated for each day, then the mean and standard deviation were calculated, these values are now reported in the manuscript (section 3.1, pg. 14, lines 482 to 487). We explain how these numbers are calculated in the SI section S3 (lines 111 to 114). This re-calculation slightly changes the percentage differences in annual mean leaf-level stomatal conductance, but the direction of change remains the same, i.e. MED increases water-use for BT and C3, and reduced water-use for NT, C4 and SH. The standard deviations are quite large reflecting the large spread in the data, partly due to the seasonal cycle.

RC11)Line 352-353, For the broadleaf tree and C3 herbaceous PFT, the Medlyn model simulates a larger conductance and therefore a greater flux of O3 through stomata compared to Jacobs, but it also led to a greater flux of CO2 through stomata simultaneously, which may be helpful for increasing photosynthesis.

AC: Figures S7 and S8 (top rows) show 1:1 plots of Anet, plotting MED (y axis) against

JAC (x axis). These plots show that in the model, Anet is not as sensitive to the change in gs scheme as gs itself (Fig. 2 and Fig. S6). Although the greater conductance for BT and C3 with MED will result in high internal CO2 concentrations, this doesn't result in a large change in modelled photosynthetic rates because in the model, the sensitivity of the limiting rates of photosynthesis to changes in ci is much lower that the sensitivity of gs to the same change (see section 3.1, pg. 14, lines 488 to 490 where this is mentioned). Therefore, the WUE for BT and C3 will change, they are less WUE with MED.

RC12)Line 366-368, Some Boreal and Mediterranean regions show increased GPP over this period, associated with O3 induced stomatal closure enhancing water availability. But O3 induced stomatal closure also reduce the flux of CO2 through stomata simultaneously, which have a negative impact on GPP.

AC: This is a trade-off between the opposing effects of O3 induced stomatal closure enhancing soil water availability and also reducing GPP. The overall effect occurs seasonally, which is not shown in Figs. 4, 5, & 6. O3 induced stomatal closure occurs during spring/early summer when O3 concentrations are highest, at this point GPP is reduced, but in these dry regions this leads to increased soil moisture that, in the model, allows growth later in the year when conditions are still favourable but soil moisture may otherwise have been limiting. We have clarified this point in the text (section 3.3, pg. 16, lines 534-538): "Some Boreal and Mediterranean regions show small increases in GPP over this period, associated with O3 induced stomatal closure enhancing water availability in these drier regions (Fig. 5). This allows for greater stomatal conductance later in the year when soil moisture may otherwise have been limiting to growth (up to 10%, Fig. 6), and therefore higher GPP, but these regions comprise only a small area of the entire domain."

RC13)Line 373-375, is the different response of GPP to low and high plant O3 sensitivity are significant?

AC: On the advice of the reviewer, we carry out statistical testing of the different responses of GPP to the low and high plant O3 sensitivities. We use the software R, and use paired t-tests to determine whether the O3 effect on GPP is significantly different between the two different plant sensitivity parameterisations (section 3.3 line 531; section 3.4 line 570; section 3.5 line 597).

RC14)Line 437-440, CO2 induced stomatal closure can help alleviate O3 damage by reducing the uptake of O3, but it will also increase available soil moisture simultaneously.

AC: We agree. The CO2 induced stomatal closure is the dominant effect that helps alleviate O3 damage. Figures S14 and S15 show that in the model the effect of CO2 on gs is large, whereas the effect of CO2 on soil moisture availability (fsmc in these plots) is small in comparison. Simulated gs declines with increasing CO2 which may increase available soil moisture, however CO2 enhances GPP and growth of the vegetation which can increase LAI leading to higher water-use on a leaf area basis. These responses are all captured in our simulation however with both CO2 and O3 changing, and in our calculation of the O3 effect with CO2 rising. We look at the difference in this simulation to the simulation with O3 changing but CO2 concentration fixed at pre-industrial concentrations, this gives us the alleviation of O3 damage by increasing CO2 and all associated effects, such as changes in soil moisture, but it is the effect on stomata that dominates. We have clarified the calculation of the alleviation of O3 damage by increasing CO2 in the legend to Table S6.

AC15)Contradictions are reported in Figure 4 and 5. In Figure 4a, the areas with great increasing in plant available soil moisture have less change in gs in Figure 5a. Why? In figure 4c, the areas with decreasing in plant available soil moisture have large reduction in gs.

AC: The fsmc formulation (factor determining plant available soil moisture) varies with soil moisture content and is non-linear. It has a value of zero below wilting point then

linearly increases to a value of 1 at field capacity, and remains at this value beyond. The wilting point and field capacity depend on soil texture. Therefore a small percentage change in soil water content in dry regions (Mediterranean) can result in a large percentage increase in fsmc. Likewise an increase in soil moisture in mesic areas (e.g. northern Europe) may translate into relatively small percentage changes in fsmc.

In Figs 5a and 6a, the areas that see a large increase in plant available soil moisture see a small increase in gs (up to 10%). This is looking at the change over the period 1901 to 2001 when only O3 is changing. Over this period there is a large increase in O3, so the O3 induced stomatal closure is large, causing the increase in fsmc in this region. The changes are seasonal, these plots show the annual mean which will average out some of the change. In this region, for example, gs increases a lot in JJA and DJF, but there is minimal change in SON/MAM. Figures 5c and 6c are for a different time period, 2001 to 2050. Over this period the O3 effect is reduced considerably, so by 2050 plant available water is reduced on 2001 levels because the O3 induced stomatal closure is less. Stomatal conductance decreases in this region during this period.

RC16)In table 1, O3 increased GPP but decreased land carbon over the period 2001-2050. Why does land C decrease when GPP is increasing?

AC: We refer to this in the results section (section 3.4, pg. 17, lines 585 to 589). GPP is a fast flux, whereas the land carbon store is a slower pool of carbon, it takes longer for this carbon store to adjust to changes in the flux, especially when those changes are fairly small as is the case here. This highlights the importance of using a carbon cycle model to look at the impacts of O3 on the terrestrial biosphere.

RC) The discussion could be improved by using subtitles more clearly.

AC: We have amended this and added subtitles.

RC17)Line 525-541, the authors listed a lot of results from the literatures, but the reader is left to decide what and why is the difference between this study and previous studies? More discussion on comparing this study with previous studies in detail would be helpful.

AC: This paragraph discusses findings from field-based studies looking at plant O3 impacts. We have removed this paragraph and put it in the introduction as it seemed more appropriate here to place our study in context (pg. 4, lines 134 to 157).

Refs: Logan, J. A., Staehelin, J., Megretskaia, I. A., Cammas, J. P., Thouret, V., Claude, H., De Backer, H., Steinbacher, M., Scheel, H. E., Stübi, R., Fröhlich, M., and Derwent, R.: Changes in ozone over Europe: Analysis of ozone measurements from sondes, regular aircraft (MOZAIC) and alpine surface sites, Journal of Geophysical Research, 117, 1-23, 2012. Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Chan, E.: Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes, Atmos. Chem. Phys., 12, 11485-11504, 10.5194/acp-12-11485-2012, 2012. Simpson, D., Arneth, A., Mills, G., Solberg, S., and Uddling, J.: OzoneâĂŤthe persistent menace: interactions with the N cycle and climate change, Current Opinion in Environmental Sustainability, 9, 9-19, 2014.

Please also note the supplement to this comment:
https://www.biogeosciences-discuss.net/bg-2017-409/bg-2017-409-AC1-supplement.pdf

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