Review of "Thirty-eight years of CO_2 fertilization have outpaced growing aridity to drive greening of Australian woody ecosystems" by Rifai et al. (bg-2021-218)

In their study, Rifai et al. analyze multi-decadal records of satellite remote sensing of normalized difference vegetation index (NDVI) and examine what role rising CO_2 is playing in driving the observed greening. The authors focus their analyses on eastern Australia's woody ecosystems and apply various (linear and non-linear) statistical methods to disentangle the key drivers of vegetation changes. Rifai et al. find that rising atmospheric CO_2 contributed to 11.7% increase in NDVI from 1982 to 2019 due to an increase in water-use efficiency, outbalancing the browning-inducing increase in aridity.

Overall, this study provides a very interesting perspective on the driver attribution of vegetation greening trends by examining statistical tools. The result that CO_2 fertilization strongly drives greening, which outpaces potential browning due to increasing aridity, is intriguing. I consider the applied statistical methods and the presented results to be robust, and the conclusions drawn to be accurate. The manuscript is very well-written and structured in a clear manner. I have a few general critical points and a rather long list of specific comments.

I recommend a minor revision of the manuscript before publication.

1 General Comments:

1.1 *You are applying various statistical methods to evaluate the effect of rising CO_2 on the NDVI trend in this study. However, it appears that you are not discussing each method to the same extend. For example, first you focus on the Weibull function (Fig. 5) and later on generalized additive models (Fig. 6 and 7). It does not become clear to the reader when and why you choose the specific models when discussing your findings. Please elaborate why you chose all these statistical models in your research in the first place and why you focus only on specific ones when discussing certain results. Otherwise, why don't you compare the results of all the statistical models you use?*

1.2 *The title and conclusion suggest that rising CO_2 could mitigate the adverse effect of increasing aridity on vegetation. Through the whole paper you thus make the assumption that increasing aridity leads to browning. I think you should show explicitly that this assumption holds. You used several statistical models to quantify the effect of CO_2, so you could reconstruct NDVI patterns without it and see how Australian woody ecosystems would look like without CO_2 fertilization.*

1.3 *The WUE model used here might be a too simplified representation of the studied processes. First, it focuses on atmospheric dryness and ignores soil dryness, i.e. soil moisture is not taken into account in this model. Second, the assumption that all CO_2-induced greening is due to increased WUE is also limited. Part of the vegetation greening could also be driven by increased productivity due to the RuBisCO-machinery response to CO_2 (Walker et al., 2021). Can you elaborate why your theoretical WUE model*

is sufficient to explain the observed changes?

2 Specific Comments:

2.1 *Please stick to the tenses, i.e. do not switch between present and past tense when describing your results. I recommend that you always use present tense when talking about your study, i.e. when describing your methods, your results etc., and use past tense when referring to already published studies.*

2.2 *You have some issues with your BibLaTeX / BibTeX setup. Sometimes brackets are missing, sometimes there are too many. Sometimes the "year" is missing in your citation (e.g. L25), or the BibTeX key does not work at all (e.g. L260).*

2.3 *L32: You show different seasons in Fig. A2, which you don't discuss here. Better to refer to Fig. 2 here, right?*

2.4 *L40: Don't understand why you refer to Zhu et al. (2016) here. They did not show that the attribution is challenging, they rather reported successful attribution results and state that most of the "greening" can be tied to CO_2 fertilization. A recently published study by Winkler et al. (2021), for example, showed that the attribution of CO_2 effect is challenging in observations / remote sensing.*

2.5 *L43-44: You write "The greening trend is caused by increased leaf area, which has resulted from increased atmospheric CO_2 concentrations". This statement reads as an absolute finding. In the sentence before, however, you write that the attribution is challenging. Can you clarify?*

2.6 *L54: Cortés et al. (2021) also show that testing for significance crucially depends on subjectively chosen criteria. One can set up a significance test such that no grid cell exhibits a significant trend, and probably the opposite: all trends are significant! I'm just wondering where we advance our scientific understanding there. I think the question is whether an observed trend, significant or not, is consistent with our expectations based on our understanding of the processes, or is it plausible in terms of our understanding of the system? If not, are we missing something? If yes, let's investigate what could be driving the trend! This is less a comment to your study, but overall to the discipline of studying greening trends and others.*

2.7 *L56: Another aspect is whether modeled LAI and observed LAI is really the same thing, conceptually.*

2.8 *L66-70: Here, you should include the fact that you approach the problem with different statistical methods.*

2.9 *L85: Have you also used other estimates, daily mean, daily max value and checked the sensitivity of your methods to this decision?*

2.10 *L95: What Organization? Please check all citations and references throughout the paper!*

2.11 *L95: Please specify the acronym MI.*

2.12 *L102: 0.05° is quite a high resolution for the AVHRR reflectances. Can you shortly note here, how this was made possible?*

2.13 *L127: Please follow the guidelines for math notations: https://publications.copernicus.org/for_authors/manuscript_preparation.html#math*

2.14 ***2.4 Estimating contribution of CO2 and climate toward NDVI trends**: Can you be more precise and say how many approaches to statistical modelling you implemented here, and why you chose these? It seems you have fitted 5 different stats. models? If so, why are you not discussing all of them to the same extent?*

2.15 *L150: You write "The relationship between NDVI and the running 12-month mean of P:PET **was** strongly nonlinear..."; shouldn't it rather read "**is** nonlinear", right? Please see also comment 2.1.*

2.16 *L155: Weibull function should refer to Fig. 5 instead of Fig. 4, right?*

2.17 *L156: "We focus on the Weibull..." Are the Weibull models fitted for each grid cell? Please specify in the method section.*

2.18 *L186 & L189: ":" before instead of "." after "follows"*

2.19 *L260: You mix a bit the Results and Discussion section, e.g. in the Results sub-section "**3.2 Empirical attribution of the CO_2 effect**" you already discuss other studies and put your results in perspective. That should be part of the Discussion sections. Either you clearly separate Results and Discussion, or you merge them completely to one section.*

2.20 *L304: It might be interesting to discuss also the results of a recent study by Winkler et al. (2021). They approached the problem of CO_2 fertilization attribution using a different approach based on causal theory, also looking into Australian vegetated lands to some extent.*

2.21 *L345: Maybe this is because you did not take into account the RuBisCO response to CO_2, which is taken into account in biosphere models (Walker et al., 2021).*

2.22 *L347-349: Maybe another limiting factor such as nutrients could kick in.*

2.23 *L383: "Some may question the veracity... ". This formulation is a bit vague: are there some studies that indicate that the veracity is limited?*

2.24 *Equation 7: Are the variables (e.g. CO_2) in the linear model normalized or not? It's important to know to what extent the coefficients of the different predictor variables are comparable. Please specify.*

2.25 *L195: A is leaf level carbon assimilation...*

2.26 *Equation 11: Is D the same term as VPD in other equations? Please use consistent abbreviation.*

2.27 *Equation 13: no definition for parameter "L"*

2.28 *Equation 16: no definition for parameter "F"*

2.29 *L290: a missing closing bracket*

2.30 *L317: There is no Fig. 6(a).*

2.31 *Figure 3: Why not show AVHRR record for the second time period?*

2.32 *Figure 5 (a): No explanation of the calculation of CO_2 and ΔNDVI (%) in the method section.*

2.33 *Figure 5, caption: "... are plotted in gray for panels B and C" should be "panels (c) and (d), right?*

2.34 *Figure 6: Can you explain why some models predict a mean negative change in NDVI with rising CO_2 – is this plausible, or is this only due to stats. uncertainty. If the latter is true, how does that generally impact on the reliability of your estimates?*

2.35 *Figure 6: Why are you only comparing two different methods here? As I understand reading your methods section, you are using more than two stats. modeling approaches.*

2.36 *Figure 7: Can you show predictions for NDVI without CO_2 – it's interesting to see the effect of intensifying aridity in the absence of CO_2 fertilization; are the ecosystems browning then?*

2.37 *Figure 7: Can you be more explicit about the labels: Does "Tropical" mean "Tropical Forests"? What is Temperate Tas.?*

2.38 *Figure 7 caption: Please use the LaTeX math mode correctly. Math-mode is always putting the text in itatlic, but this is not correct most of the time. This introduces also some inconsistencies in your manuscript, e.g. you put NDVI in non-itatlic but ΔNDVI in italic. Also units and chemical formulas like CO_2 etc. should not be typeset in italic! Please see also comment 2.12.*

2.39 *Figure 7: Are the captions missing for panels (d) and (e)?*

2.40 *Figure 8a: Can you provide some estimate of uncertainty for the different regression lines, e.g. the standard error? How robust are these linear trends?*

2.41 *Figure 8c: I don't get your biome definition really. What is "Tree Vegetation" in "Grassland"? Are you showing the shifts from non-woody to woody species composition here?*

2.42 *Figure 8 (c): "The 25, 50 and 75% quantiles are overlaid." However, in some distributions, there are only 1 or 2 lines.*

2.43 *Figure A9: According to L214, your theoretical assumption only holds as long as LAI <= 3. The values in x-axis in Fig. A9, however, exceed 4. How does that impact your analysis here?*

2.44 *Figure A2: This figure could be extended with another panel for P/PET.*

2.45 *Figure 3. One idea could be to move Fig. 3(a) to Fig. 2., and add another supplementary figure instead. This one could include Fig 3 (b), (c) and the merged NDVI between 1982-2019 for each season.*

References

Cortés, J., Mahecha, M. D., Reichstein, M., Myneni, R. B., Chen, C., and Brenning, A. (2021). Where Are Global Vegetation Greening and Browning Trends Significant? *Geophysical Research Letters*, 48(6):e2020GL091496.

Walker, A. P., Kauwe, M. G. D., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R. F., McMahon, S. M., Medlyn, B. E., Moore, D. J. P., Norby, R. J., Zaehle, S., Anderson-Teixeira, K. J., Battipaglia, G., Brienen, R. J. W., Cabugao, K. G., Cailleret, M., Campbell, E., Canadell, J. G., Ciais, P., Craig, M. E., Ellsworth, D. S., Farquhar, G. D., Fatichi, S., Fisher, J. B., Frank, D. C., Graven, H., Gu, L., Haverd, V., Heilman, K., Heimann, M., Hungate, B. A., Iversen, C. M., Joos, F., Jiang, M., Keenan, T. F., Knauer, J., Körner, C., Leshyk, V. O., Leuzinger, S., Liu, Y., MacBean, N., Malhi, Y., McVicar, T. R., Penuelas, J., Pongratz, J., Powell, A. S., Riutta, T., Sabot, M. E. B., Schleucher, J., Sitch, S., Smith, W. K., Sulman, B., Taylor, B., Terrer, C., Torn, M. S., Treseder, K. K., Trugman, A. T., Trumbore, S. E., van Mantgem, P. J., Voelker, S. L., Whelan, M. E., and Zuidema, P. A. (2021). Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. *New Phytologist*, 229(5):2413–2445.

Winkler, A. J., Myneni, R. B., Hannart, A., Sitch, S., Haverd, V., Lombardozzi, D., Arora, V. K., Pongratz, J., Nabel, J. E. M. S., Goll, D. S., Kato, E., Tian, H., Arneth, A., Friedlingstein, P., Jain, A. K., Zaehle, S., and Brovkin, V. (2021). Slowdown of the greening trend in natural vegetation with further rise in atmospheric CO_2. *Biogeosciences*, 18(17):4985–5010.

Zhu, Z., Piao, S., Myneni, R. B., Huang, M., Zeng, Z., Canadell, J. G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T. A. M., Stocker, B. D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., and Zeng, N. (2016). Greening of the Earth and its drivers. *Nature Climate Change*, 6(8):791–795.